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Review of Experimental Observations
About the Cold Fusion Effect

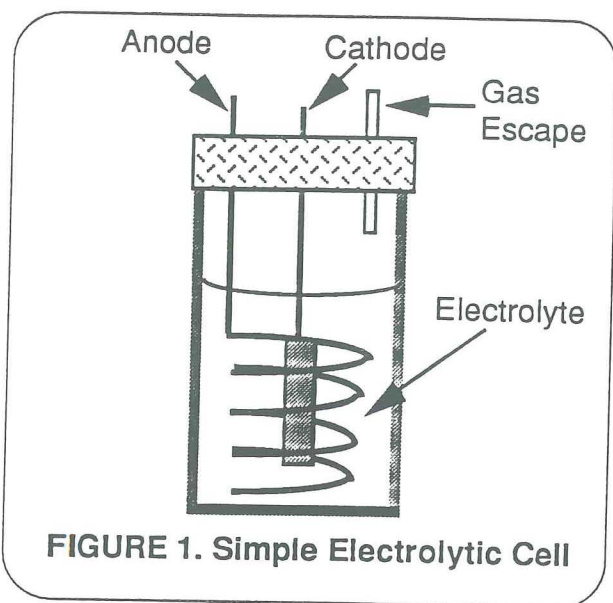
by

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other salts. The container is designed to prevent atmospheric contamination but with a vent to allow escape of generated gas. This arrangement is called an "open" cell and is drawn to show the simplest configuration in Fig. 1. When a catalyst is placed in the assembly to recombine the generated gases, the cell can be completely sealed and a "closed" cell is created. Direct current of various magnitudes is passed between the electrodes so that D_2 is formed at the cathode and O_2 is produced

at the anode. Because of the applied voltage, very high effective pressures can be generated within the metal¹ and the ions are given a modest energy. This very chemically active deuterium reacts with the palladium or titanium cathode to form a hydride having a high but variable stoichiometry that depends on a complex set of circumstances. The stoichiometry that is achieved in localized regions appears to play a role in making the effect occur. Many variations on this basic design have been reported. Excess heat, neutrons, protons, and tritium have been detected using this method, although not all at the same time. A sudden change in charging current seems to trigger the Cold Fusion effect. However, initiation also has been observed without this abrupt change.

Electric Current in Gas Containing Cells [236; 247; 252; 304]: A voltage sufficient to produce gas discharge is placed between electrodes in low-pressure deuterium gas. This process gives the deuterium ions more energy than they can achieve in an electrolytic cell. Both palladium and titanium have been used as the cathode. Unexpectedly large amounts of neutrons, tritium, and excess heat have been detected, but not all in the same experiment. One study has achieved tritium and neutron production by passing pulsed current through alternating layers of Pd and Si discs[252] in high pressure D_2 gas. This is a combination of gas discharge and direct gas reaction.

1. The magnitude of the pressure can be calculated using the Nernst Equation. However, the very nonideal nature of the solution must be taken into account to obtain the correct pressure.

Ion Bombardment and Implantation [173; 174; 175; 186; 196; 208; 248; 278; 281; 299; 300]

[305; 306]: Ions and molecules are accelerated to various energies and impacted on various target materials. This technique not only implants deuterium into the metal lattice to give a very high D/metal ratio, but also can produce ion energies that approach those used in hot fusion. Neutrons, tritons, and protons have been detected that, in some cases, were in greater quantity than expected. Implantation of hydrogen in metals has been reviewed by Myers et al.[307].

Typically, all of the above conditions produce bursts of nuclear products sometimes superimposed on a relatively steady lower production rate. This behavior implies a nonequilibrium state[37; 270; 279; 308; 309; 310] and/or two independent processes. Apparently, suitable conditions can be imposed by changing the environment or are produced as a natural consequence of electrolytic action. Note that electrolysis may appear steady in a macro sense but the conditions are nonequilibrium when viewed on a micro level. Bubble formation produces chaotic regions in which the electrolytic reaction is turned off and on, thereby rapidly changing the chemical environment of the surface. Erratic formation of bubbles, microcracks and dislocations make the interior of the metal very complex. These factors, by themselves, would make the phenomenon very difficult to reproduce. Indeed, most normal physical and chemical processes involving palladium are frequently difficult to reproduce.

Apparently, the creation of some types of special conditions are essential if the nuclear effect is to occur at all. Reproduction of these special conditions is the primary problem in making a general study of the nuclear processes possible. Although many workers who have continued to study the Cold Fusion effect have been rewarded by increased reproducibility within their own laboratories, a universal recipe does not seem to exist. Just too many unknown and, therefore, uncontrollable variables exist. However, there are quite a number of conditions that are now known not to produce positive results. Some of these insights will be examined.

An important special condition that must exist for any of the nuclear reactions to be initiated is the presence of high, local concentrations of deuterium as previously suggested[1; 311]. This view is widely accepted. Such high concentrations have been proposed to be associated with regions of stress[276; 312], to be enhanced by surface or bulk impurities, and associated with phase changes[313]. On the other hand,

deuterium concentration can be reduced by excessive microcracking or by normal hydrogen in the metal[314]. Generally, these high concentrations are expected to occur at or near the surface, especially during electrolytic charging or ion bombardment. These considerations as well as many observations suggest that tritium production occurs mainly at the surface for both titanium and palladium. Heat and neutron production are not so easily located in this respect. Nevertheless, many workers still propose that the heat reaction occurs within the entire volume of the electrode. Consequently, they report heat production as energy/cm³ or energy/mole. This gives the impression of much greater energy release than actually occurred from the small cathode volume used in the cell. This approach also underestimates energy density within the few active regions.

From the first, the D-D fusion reaction was thought to be the most likely source of nuclear products, although other possibilities have been proposed. This reaction has two branches that have been measured at high energies, yielding an almost equal probability. These branches are $D + D = {}^3\text{He}(0.82 \text{ MeV}) + \text{neutron}(2.45 \text{ MeV})$ and $D + D = \text{H}(3.02 \text{ MeV}) + \text{triton}(1.01 \text{ MeV})$. A third branch, $D + D = {}^4\text{He} + \gamma (23.5 \text{ MeV})$, is possible but it has a very low probability in plasma reactions. Considerable confusion and disbelief has been created by the lack of neutrons, consistent with detected tritium and heat. Data now clearly show that:

- (1) No experiment has detected sufficient neutrons or tritium to account for the reported heat[315]. Although neither tritium nor neutrons are usually detected during heat production, there is evidence that ${}^4\text{He}$ is produced[240; 177; 316].
- (2) While there is a clear relationship between neutron and tritium production, occasionally neutrons are produced without any tritium being found.

In order for these and other apparently conflicting observations to be explained, even to a limited extent, an important hypothesis is proposed. At least three nuclear reactions are proposed to occur within a metal deuteride lattice. One reaction produces the major source of heat, the second produces mainly tritium with a few neutrons giving a $n/{}^3\text{H}$ ratio near 10^{-9} , and the third, appears to produce mainly neutrons. Which of these operates at any time depends on the special conditions that exist at that time. Of course, more than one of these reactions could occur at the same time but at different locations in the metal. Additional reactions have been suggested

but the evidence is less compelling. Detailed experimental justification for this suggestion and a model that combines the various mechanisms and nuclear reactions is developed in this review. The experimental studies for heat, tritium, neutron, γ -ray and ^4He production will be discussed starting with heat production.

II. EXCESS HEAT PRODUCTION

Four major logic-levels are associated with understanding the source of excess heat. The first level asks the question:

1. Is the excess heat caused by errors in the measurement?

This possibility will be discussed in Section II.A. Should the answer be "no", the question at the next level is:

2. What is the reaction that produces excess heat?

As the amount of observed excess energy increases beyond a certain level, the probability for a nuclear origin increases as well. At some level, there is no possibility of evoking a chemical source without major conflict with basic chemical experience. This experience shows that there is an upper limit to the energy that can be obtained from a chemical bond. Thus, there is an upper limit to the energy that can be obtained from the limited quantity of chemicals that exist in a cell. This assertion will be discussed in Section II.B. If the amount of heat is sufficiently large and nuclear products are found, the question becomes:

3. What nuclear reaction produces the excess energy?

Conventional fusion theory predicts a trivial fusion rate at room temperature. Consequently, if a significant fusion rate does occur, it must be caused by an unexpected phenomenon involving special conditions that exist in a periodic array of metal atoms. Several theories have addressed this aspect but will not be discussed in this review. The question at the next logic-level is:

4. What is the new phenomenon, how can it be initiated in the lattice, and what nuclear reactions are influenced by the phenomenon?

At this level of acceptance, we are dealing with an approach normally applied to a mature science. As yet, the Cold Fusion field has not reached this level in some people's minds

Efforts to attribute the heat to a chemical source have taken three forms: (1) the calorimeter has a positive bias because energy accounting has not been properly made, (2) energy is accumulated in some chemical form during the initial charging and released later, and (3) an unknown reaction releases the energy. The latter source is proposed to be either mechanical or chemical.

II.A Errors in Calorimetric Measurements

One needs to appreciate that the technique of calorimetry is very highly developed, being used with increasing accuracy for over 100 years. While an individual may make a mistake or an apparatus may fail in some respect, these problems are not common within the field of expertise. Nevertheless, all measurements contain some error. Error analysis depends on the type and design of the calorimeter used. However, in all cases, the errors can be divided in two groups. These are (1) random errors that relate to the precision of the various individual physical measurements needed to arrive at the excess heat, and (2) systematic errors that occur because some energy has been ignored in the calculation, owing to design defects or unknown chemical reactions. Both types of errors are normally revealed by studying cells containing H_2O as the electrolyte, using Pt as the cathode instead of Pd, or inactive cells containing both D_2O and Pd. If such cells show no excess heat above that which can be accounted for by considering all energy entering and leaving the cell, the calorimeter is generally considered to be accurate to the degree that input power equals measured power.

The most important systematic errors involve energy that leaves the cell. When gases escape, there is an uncertainty in the chemical energy carried away by the resulting hydrogen and oxygen because of possible partial recombination within the cell. However, all of the workers reporting excess heat are aware of this problem and, when tested, recombination is found to be negligible at currents above 30 mA/cm^2 [317] and as long as the electrodes are kept below the fluid surface [147; 151; 152]. Dissolved hydrogen and oxygen can be recombined on the anode but the rate is trivial [318]. Furthermore, many workers now place a recombiner within the cell so that no gas need leave and all of the chemical energy remains in the cell. An additional factor is the transport of D_2O vapor out of the cell with the gases [147; 224]. Heat associated with this loss is small when the cell temperature and current are low but become sig-

nificant when both are large. This quantity needs to be included in the heat calculations when the highest accuracy is desired. Some $\text{LiOD}+\text{D}_2\text{O(l)}$ mixture is also carried away as an aerosol within the gas stream. This effect increases as the current is increased but is small under most conditions. Of course, none of these processes is important when a closed cell is used.

Energy deposited within a cell is in the form of an electric current and is calculated by multiplying the current passing through the cell by the voltage measured between the electrodes. This energy can be determined with very high precision provided both current and voltage are measured as a function of time. Once the cell is assembled and turned on, energy flow is monitored and any subsequent energy entering the cell will be detected within limits determined by known errors. Although some workers have charged the palladium at low current without monitoring the energy during this time, most excess heat has been found after a complete accounting was made from the time the cell was first turned on.

Besides the electric current, chemical reactions and physical strain may add energy to the cell.

II.B Chemical Sources of Excess Heat

Typical cells contain a very limited number of elements and amount of material. Therefore, the total, possible excess mechanical or chemical energy contained in these materials or produced by interaction also must be equally limited. Only energy above the lowest possible energy states of the initial constituents of the cell is available to be added to energy that is generated within the cell. The only additional substance that is normally added is D_2O to replace that which is lost by electrolysis from an open, unsealed cell. Deuterium oxide is generally acknowledged as being in its lowest chemical state under these conditions. Furthermore, all of the construction materials are chemically inert to each other when allowed to remain in contact over a long time. Therefore, for a chemical reaction to occur, some form of energy must be supplied from the outside. In this case, this energy is supplied by the electric current.

Only three current-induced chemical reactions are known to have the potential to affect the energy balance to a significant extent. These are the formation of D_2 and O_2 gases from the heavy-water (Section II.E.3), formation of PdD_x at the cathode

with the release of O_2 gas, and formation of Pd-Li alloy at the cathode by reaction with lithium ions. Peroxide formation has been proposed but not detected.

The formation of β -PdD by a reaction between Pd metal and deuterium gas [38; 319; 320] and chemisorption on internal cracks [321] gives off heat. This source of heat is discussed in detail by Godshall et al.[149]. An observed increase in cathode temperature during the initial reaction to form PdD and a decrease during removal of deuterium is consistent with expectations[231; 241]. An initial cooling of the cell also has been reported[157; 228; 231] that is not caused by the Peltier effect[156]. However, as the palladium cathode becomes saturated with deuterium, this relatively small energy perturbation decreases and the temperature of the cell returns to a baseline value.

Elemental palladium and lithium form an alloy with heat release. However, the reaction in a cell is between Pd and Li^+ ions in solution. This reaction requires energy which, again, is supplied by the flowing current. Consequently, a slight temperature reduction would result to the extent that such an alloy formed. This temperature reduction is not observed because the rate of formation is limited by the diffusion rate of Li in Pd, a very small number.

In summary, any chemical reaction that requires additional Gibbs energy supplied by the flowing current in order to occur, will appear as a loss of energy from the cell. Should such a normally unstable compound be formed but go unnoticed, a heat effect would occur when the cell current was subsequently decreased or stopped, thereby allowing the compound to decompose. Only one such heat effect has been reported[225], but at a level much too small to suggest this effect could be the cause of significant excess heat. Thus, critiques that explain the excess heat as owing to the formation of hypothetical compounds are not consistent with observation[135; 322]. An analysis of possible chemical reactions was developed soon after the first announcement of the Cold Fusion effect and should be consulted for more detail[323].

The palladium can contain some strain energy that would be released during hydriding[324]. While the amount of this energy is difficult to quantify, it is expected to be small[325] and would be released and measured only during the initial hydriding process. Excess heat lasting weeks has been detected even when fully annealed, strain-free Pd was used. Should strain energy be introduced and subsequently released during hydriding, no excess heat would be seen because the energy would be

part of the measured heat balance within the calorimeter. Consequently, the expected behavior of strain energy, either initial or induced, is not consistent with observation.

Another approach can be taken to put the chemical-mechanical source of heat in perspective. The amount of reported excess energy can be compared to various chemical and physical processes. As much as 50 MJ/cm^3 ² of palladium has been reported to be released during the life of a cell[224]. This amount of energy is sufficient to melt 641 cm^3 or 7690 g or 72 moles of palladium at 1825 K[326], and its production would require 1700 g of hydrogen to be burned. If released during a short time, this energy would raise a typical cell (<1 kg of glass and heavy-water) to >12,000 K. Of course, only a few cells have achieved this much excess energy production and, fortunately, it occurred over many weeks. Nevertheless, the above examples of common chemical and physical processes show how difficult it is to attribute this amount of excess energy to a nonnuclear process. The only other alternative is to argue that a large positive and variable bias exists in all calorimetry measurements giving positive results. This suggestion is not supported by any other behavior pattern in the measurements.

II.C Examples of Experimental Results for Excess Heat Production

Table 1 compares the various reported heat measurements, both positive and negative, and lists the accuracy for the calorimeter when a value is reported. Each entry generally represents several examples of positive and/or negative results. The presence of excess heat was usually not claimed until the accuracy limit was exceeded. On average, the calorimeters that produced negative results have lower accuracy than those that gave evidence of excess heat. Nevertheless, they should have been sufficiently sensitive to see heat if it had been produced. Absence of heat is proposed to be caused by unfavorable conditions that existed in the palladium cathode. This aspect will be discussed in a later section.

2. This reported value assumes that energy production is proportional to the volume of the electrode. This assumption may not be correct. It is not clear from the paper just how much total energy was produced in this experiment. If the smallest reported electrode volume of 0.01 cm^3 is assumed, the total energy would be about 0.5 MJ. When this quantity is used, subsequent calculated values need to be reduced by a factor of 100. In spite of this uncertainty, chemical sources of energy are still very unlikely.

TABLE 1

Summary of Calorimetry Studies

REFERENCE	CATHODE	TREATMENT	TYPE	OPEN or CLOSED	BLANK yes-no	ACCURACY
NO EXCESS HEAT REPORTED						
Albagi	1mm wire	725° vac	isothermal	O	Y	≈5%
Armstrong[158]	sheet	?	flow	O	Y	<4%
Bosch[159]		melted	heat loss	O	N	5%
Chemla[154]	1mm wire	?	heat loss	O	Y	3-5%
Fleming[183]	0.5-3mm, melt cast, hot pressed	anodized, vac	Seebeck	O,C	Y	2%
Godshall[149]	cast	900° vac	vapor	O	?	2%
Hayden[144]	investment	600° vac	flow	C	Y	0.3%
Iyengar[247]	tube	sanded	adiabatic	O	Y	?
Jow[146]	1,0.5 mm	1140° vac	Seebeck	O	Y	2%
Keesing[156]	1 mm wire	≈1400°	substitution	O	N	1%
Kreysa[137]	sheet, 1cm rod	?	heat loss	O	N	5%
Lewis[148]	0.25-3.9 mm wire	sanded, melted	isothermal	O	Y	<6%
Longhurst[153]	51μm foil, 1mm wire	?	heat loss	O	Y	5%
McCracken[155]	sheet,rod,tube, Ti Sponge	600° vac	flow	C	Y	1%
Miskelly[133]	2.2, 3.9mm wire	?	heat loss	O	Y	5%
Redey[151]	6.3 mm wire	650° air, 600° vac	heat loss	O	N	0.3W
Ritley[165]	6 mm wire	variety	heat loss	O,C	Y	0.4W
Stilwell[152]	1.4 mm wire	245°	heat loss	O	Y	5-10%
Wiesmann[147]	rod, sheet	300° vac	heat loss	O	Y	≈0.5W
Williams[157]	1-6 mm wire, bar, cast, ribbon	?	heat loss, isothermal	O,C	Y	5-10%
EXCESS HEAT REPORTED						
Appleby[226]	0.5,1 mm wire	none	Seebeck	O	Y	<1%
Arata[241]	2 cm rod	?	cathode T	O	Y	na
Droege[230]	2 mm wire	?	isothermal	C	Y	≈0.5%
Eagleton[327]	investment	aqua regia 200° air	flow	C	Y	0.3W
Gozzi[231]	powder	sintered	cathode T	O	N	na
Guruswamy[244]	Pd,Ti,Zr	600° Ar	heat loss	O		?
Huang[246]	coin	arc-melted	flow	O	N	0.05
Hutchinson[227]	6.3 mm, 1.3 cm	900° vac, 200° vac	heat loss	O	N	?

Table 1, Continued

REFERENCE	CATHODE	TREATMENT	TYPE	OPEN or CLOSED	BLANK yes-no	ACCURACY
Kainthla[232]	1,3 mm wire	electro.	heat loss	O,C	N	3%
Karabut[236]	disc	?	heat loss	gas	Y	?
Lewis[242]	3 mm bar	900°	flow	O	Y	0.2W
Liaw[234]	wire	torch	heat loss	O	Y	?
		melted	Fused salt			
McKubre[225]	rod	melted, 800° vac	flow	C	Y	0.2W
Miles[243]	6.3 mm wire	?	heat loss	O	Y	5%
Noninski[237]	0.5 mm wire	?	adiabatic	O	N	0.1%
Oriani[238]	1 mm wire	none	Seebeck	O	Y	0.3%
Pons[1;224]	1,2,4,8 mm	none	heat loss	O	Y	<1%
Santhanam[239]	Ti and Pd	?	substitution	O	N	?
Schreiber[228]	old crucible	melted, hammered	heat loss	O,C	Y	<1%
Scott[229]	5.6,2.8 mm	900° vac	flow	O,C	Y	1-3%
Szpak[245]	electrodeposited Pd		heat loss	O	Y	?
Yang[235]	6, 3.5, 2.2 mm	600° Ar	heat loss	O	?	?
Zahm[163]	4 mm wire	?	heat loss	O	N	?

Explanation of Headings

CATHODE: All cathodes are palladium except when noted. A few examples of size are given even though cathodes of various length, mass and area were frequently used.

TREATMENT: Lack of space limits the details that can be listed in this category. In many cases, the cathode was heated in vacuum at the indicated temperature. Other treatments might have proceeded this anneal. In some cases, other treatments might have been used instead of an anneal.

TYPE: A variety of calorimeter types have been pressed into service, each having its own sensitivity and absolute error. These are:

Adiabatic: Energy is measured by noting the rate of temperature change. This generally occurs so rapidly that little energy is lost to the surroundings.

Heat Loss. Energy production causes the temperature of the cell to increase until energy loss equals energy gain. The achieved temperature is used to determine the energy production rate. Several variations on this design have been used as well as various methods of calibration. A detailed analysis of this calorimeter type is given by

Table 1, Continued

Pons and Fleischmann[224]

Isothermal. A source of known energy is applied to the cell and this energy is adjusted so as to keep a constant temperature as other sources of energy change. A resistor is usually used to add this known energy. However, Droege[230] uses a thermopile.

Vapor. The cell is kept in a Freon bath which is boiling at a known rate. Changes in the boil-off rate are used to determine the energy added by the cell.

Seebeck. Heat is allowed to exit the cell through a thermopile and the generated voltage is used to determine heat flow.

Flow. Heat is carried away by flowing water. Energy change is determined by measuring the temperature difference between water entering and leaving the calorimeter. This quantity is used in combination with the flow rate and the heat capacity of water.

Substitution. A quantity of known energy is used to bring the cell to the same temperature that was achieved during electrolysis. The difference between the net energy supplied to the cell during electrolysis and the known energy is considered to be excess.

Cathode T. On a few occasions, excess heat has been determined by measuring the temperature increase of the cathode. While being sensitive to heat production, this method cannot give a quantitative value.

OPEN or CLOSED: Calorimeters not having internal recombination of the gases are considered to be open (O) even though they may be isolated from the atmosphere. Closed cells (C) recombined the D_2 and O_2 , thereby allowing no gas to escape. One study, designated "gas", used ion discharge in D_2 gas.

BLANK: Some calorimeters were run using a Pt cathode or H_2O in the electrolyte. This gives a base line for zero excess heat production and a measure of the accuracy. A "Y" is noted if such blanks were studied and "N" if not. However, very often cells that were expected to produce excess heat did not. During this time, a blank base-line could be obtained in spite of not running a formal blank.

ACCURACY: Frequently, but not always, a value for the accuracy was noted in the paper. Generally, the sensitivity was less than this value. No excess heat was claimed by the authors unless the accuracy limit was exceeded by an arbitrary amount.

Although all of these results have potential importance, a few studies need to be examined in detail because they are unique. In general, the heat production rate reported in these studies is so large that dismissing the results as being caused by calorimeter errors is not reasonable. Furthermore, the heat was made under a variety of conditions so that if it is caused by a chemical effect, a variety of very energetic chemical reactions must be assumed. Such an assumption is very difficult to justify.

Williams et al [157](Harwell, England): This is a very broad study using Pd and Ti from a variety of sources and several calorimeter designs. However, no evidence of excess heat, neutron, γ -ray, ^3He , ^4He or tritium production was reported. The calorimeters were sufficiently sensitive and the current range was sufficiently broad ($\leq 600 \text{ mA/cm}^2$) so the excess heat should have been detected had fusion occurred. This negative result has produced considerable skepticism about the Cold Fusion effect.

McKubre et al.[225] (SRI, USA): A high-pressure cell (60 atm D_2) was electrolyzed under conditions that prevented oxygen formation. The palladium was vacuum melted, machined, etched with aqua regia, vacuum annealed at 800°C and cooled in D_2 . Excess power between 1.5 and 2 W with bursts was reported. In addition, autoradiography found radioactivity³ in the cathode even though no evidence of tritium was found in the electrolyte nor in D_2 removed from the electrode. Helium 3 and 4 (^3He , ^4He) were not detected. However, detection sensitivity may not have been sufficient to see the amount of helium associated with the small total energy production. Surface analysis found no change in the normal isotopic ratio and no elements that might be associated with a fusion reaction. Loading near $\text{D/Pd} = 1$, based on resistivity change, was claimed but not all electrodes so loaded produced heat. Deuterium loss produced heat in one case. A deuterium gradient is suggested to be important.

Appleby et al[226] (Texas A&M, USA): A very sensitive, microcalorimeter was used to study small samples. Normal LiOD as well as material enriched in either ^6Li (98.67%) or ^7Li (99.8%) was used in the electrolyte without producing a significant difference in excess heat production rate. However, when the LiOD was replaced by NaOD, energy production decreased to zero over about 10 hrs. Subsequent replace-

3. Blanks showed no such effect. Miles and Miles[328] have calculated some possible radioactive species that might be present.

ment of the NaOD by LiOD caused excess heat to return. When the current was interrupted, excess heat production did not stop immediately but decreased rapidly at first then more slowly over several hours.

Santhanam et al.[239] (Tata Institute, India): Excess heat is claimed using 1 M NaCl as the electrolyte and Pd or Ti as cathodes. Pd gave the larger production rate. This rather incompletely described work is the only claim for excess heat using sodium in the electrolyte.

Bush and Eagleton[233] (Cal. Poly, USA): An investment bar of palladium (Englehard Industries) was used. By carefully studying excess energy production as a function of charging current in several cells, a fine structure was found in the relationship. This structure is explained by the authors using a resonance theory. **Kainthla et al. [232] (Texas A&M, USA)** measured heat production over the same current range with similar detail and reported no such structure.

Liaw et al.[234] (Univ. of Hawaii, USA): This is the first study using a fused salt of KCl+LiCl in which LiD is dissolved. Excess heat was obtained between 400° C and 460°C using Pd or Ti as the active electrode (anode). Only Pd that had been flame melted, which gave a porous surface, produced heat. Palladium gave a power production rate equal to 1512% excess at 692 mA/cm² and 460° C, a net gain of 25.4 W from 0.498 g Pd. Excess ⁴He was detected in the electrode but not enough to account for the heat. Titanium also produced excess heat but at a much lower rate. While Li is present in the solution, it reacts with the Al cathode rather than with the anode. Apparently Li does not need to be present with the deuterium for excess energy to be produced.

Karabut et al.[236] ("Lutch", Russia): Heat and neutrons were produced by using electric discharge in D₂ gas with a Pd cathode. Although this work is not reported in detail, 120-150% excess heat over the electrical input is claimed. The effect did not occur when the palladium was oxidized and when the Pd exceeded 500 K. The maximum neutron flux was about 10⁷ n/sec which, it is claimed, corresponds roughly to the heat production rate if a branching ratio (n/³H) of 10⁻⁸-10⁻⁹ is assumed.

Bush /Miles [240] (Univ. Texas and Naval Weapons Center, USA): Helium 4 was found in the effluent gas (100x detection limit) while excess heat (0.14-0.52 W) was being produced in Pd/LiOD-D₂O cells. The amount of helium was consistent

with the amount of heat. No ^4He was found when heat was not produced. This work confirms that ^4He is the nuclear product of heat production and it shows that the reaction occurs on the surface. In addition, dental X-ray film located on the outer surface of the cells showed the presence of radiation. Normal water containing cells showed neither ^4He nor radiation, although some unexplained excess heat was reported. No ^3He was detected.

Droege [329] (Batavia, IL, USA): When D_2O was replaced by H_2O , the heat continued for about 35 h then abruptly dropped to zero. **Scott et al.[229] (ORNL, USA)** found that after the electrolyte was replaced by one containing normal water, excess heat, neutron and γ ray production took over 100 h to disappear. **Huang et al. [330] (Univ. Hawaii, USA)** also found that 20-40 h were needed to eliminate excess heat after adding normal water. **Belzner et al.[331] (Stanford Univ., USA)** reported loss of heat when the electrolyte was exposed to the atmosphere. In this case, the effect could have been caused by CO_2 as well as by water pickup.

Arata and Zhang [241] (Kinki U. and Osaka U., Japan): Temperature of a large Pd cathode (2 cm $\times$ 5 cm) was measured while deuterium was caused to repeatedly enter and leave the metal by switching the cell current off and on. Production of heat during charging and cooling during discharging were clearly observed. In addition, large bursts of heat were seen occasionally as the palladium temperature rose and fell (70-110°C) while the current was constant. The magnitude of this energy is far higher than can be explained by the deuterium absorption reaction, in contrast to the conclusion reached by the authors.⁴

Lewis and Sköld [242] (Uppsala Univ., Sweden): A bar (3x3x55 mm) of Pd was electrolyzed and produced excess heat while neutron and tritium measurements were being made. In one cell, excess heat showed bursts to 155% and there were occasional neutron bursts associated with turning the cell off and on as well as just before

4. The authors conclude that the measured temperature increase of the cathode was owing to reaction with deuterium. This cannot be correct for the following reasons. The palladium was found to increase from 70° to 112° over 1.5 min. If no energy were lost to the electrolyte, this temperature change would require 460 cal, based on the sample weight and the heat capacity of Pd. At the maximum cell current of 500 mA, 4.7×10^{-4} mol of D would have been available to react with the Pd during the 1.5 min temperature increase. This would have generated about 4 cal if all had reacted. Thus, the energy generated is at least 100 times greater than the energy available from the hydriding reaction.

excess power production ceased. Onset of power production seem to be associated with D_2O additions. No excess tritium was found in the electrolyte. Another cell gave bursts of excess heat to 39% but neutron bursts were seen only after heat production had largely ceased.

II.D. Relationship Between Heat Production and Cell Current

When the steady component of heat production as W/cm^2 is compared to the total cell current as mA/cm^2 , a broad relationship is found⁵ as shown in Fig. 2.

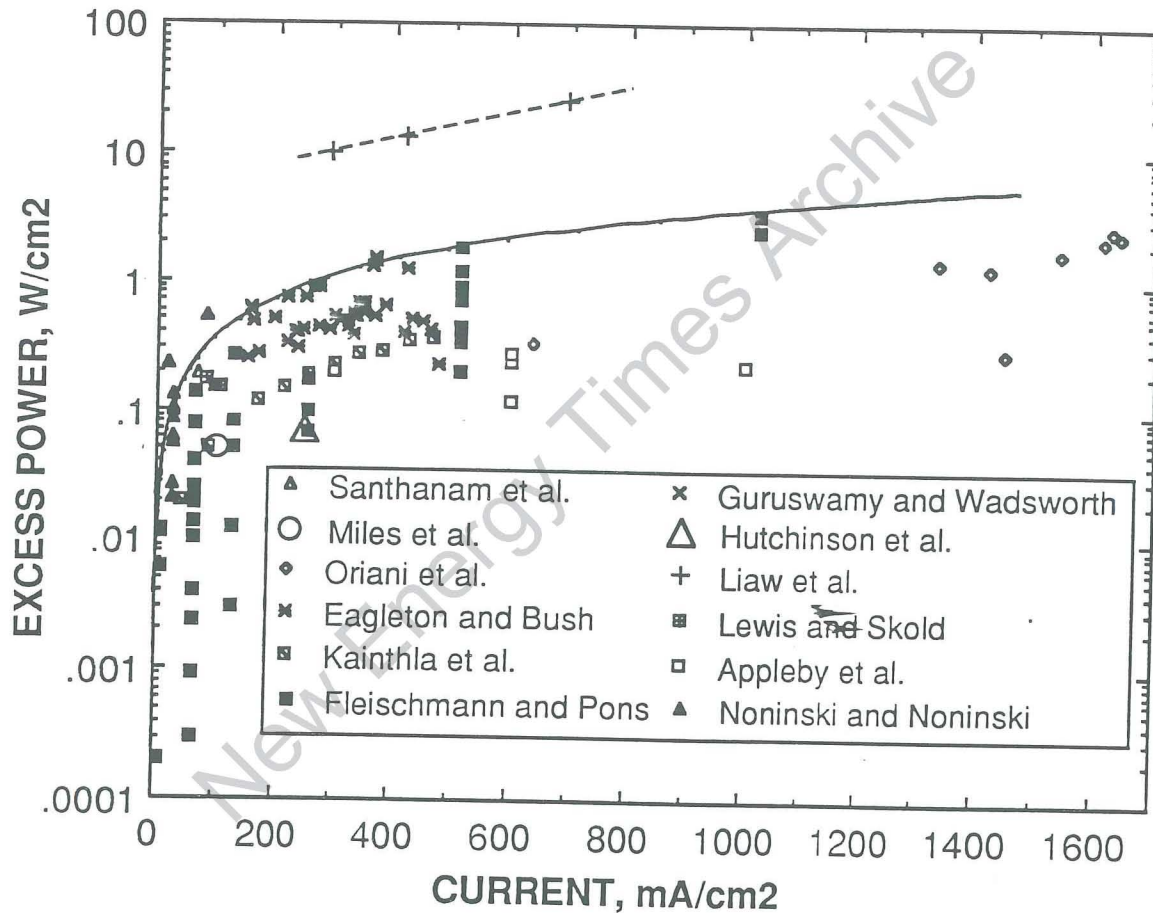


FIGURE 2. Effect of total current density on excess power per cm^2 . All values are from D_2O containing cells except Liaw et al.[234].

5. Unfortunately, not all the positive results could be compared because certain details are lacking in the papers.

As first suggested by Pons and Fleischmann[224], there is a marked increase in excess power as the current density is increased at low current density. When measurements based on a variety of cathode volumes and areas are compared, there is a suggestion that an upper limit to heat production exists at each current and that this limit approaches a constant value as current is increased. When plotted on a linear scale in contrast to the log scale shown in Fig. 2, the upper limit for an aqueous cell is described by the equation,

$$W \text{ (watts/cm}^2\text{)} = 3.6 I \text{ (ampere/cm}^2\text{)}$$

to at least 0.7 A/cm². The solid line in the figure shows values obtained from this equation. There is an indication in the data that the process may saturate at higher currents and the large scatter indicates that current density is not the only important variable⁶. Typically, large bursts lasting several minutes superimpose on the steady heat production. Fleischmann and Pons state that tritium is produced during these episodes but the details are still lacking and confirmation by other studies is mixed. Some bursts appear to produce tritium and some do not. At much higher temperatures, in a fused salt cell, Liaw et al.[234] have produced much larger steady power with a similar sensitivity to current density and a similar tendency for burst formation.

It is hard to support an argument that all of these measurements, based on many different calorimeter designs, suffer from errors that can conspire to produce this relationship. Nevertheless, there are a number of factors that need to be considered when interpreting this behavior. The following partial list also gives an example of the difficulty in sorting out variables so that reproducibility can be achieved. As the current is increased,

1. bubble coverage will increase thereby shielding a greater average fraction of the surface from the current and producing greater local fluctuation in deuterium content as bubbles are made and released,
2. the voltage across the surface layer will increase,
3. the temperature of the cathode will increase,

6. The large scatter at low current densities may be owing partly to temperature errors caused by poor mixing because of the small amount of evolving gas[150]. This is not a problem at high current where bubble generation produces good mixing.

4. the concentration of deuterium in the surface region of the cathode will increase, and
5. deposition rate of impurities will increase[332].

The order of importance that should be assigned to these variables is not clear at the present time. However, a comparison between the aqueous cells at 25-50° C and the fused-salt cell at 400-460° C strongly suggests that temperature is a major variable.

II.E. Discussion of Factors Affecting Heat Production

Although there are clearly many important variables that have not yet been revealed, a few can be suggested based on both negative and positive observations.

II.E.1 Electrolyte:

Electrolytes containing LiOD, LiOH, LiOD+Li₂SO₄, Li₂SO₄, LiOD+NaCN, or NaCl all have given excess heat on occasion. However, when LiOD was used at very high concentration in glass containers, the excess heat was not observed, perhaps because glass components deposited on the cathode surface[151]. Nevertheless, glass or stainless steel cells have been used successfully at the usual 0.1M concentration.

The effect of enriched lithium has been studied to determine whether Li-D fusion was occurring. Stilwell et al.[152] found no excess heat when normal lithium was used. On the other hand, Appleby et al.[226] produced excess heat and the amount was insensitive to whether ⁶Li, ⁷Li or normal lithium was used. When the lithium containing electrolyte was replaced by one containing sodium, the heat effect stopped[226]. Nevertheless, heat has been produced in a fused salt cell, in which Li does not enter the palladium, and heat has been reported using an electrolyte containing NaCl[239]. In addition, tritium has been produced on many occasions using a sodium-containing electrolyte[247]. Apparently, lithium is not essential to the production of tritium and perhaps not to the production of heat as well.

Any impurity in the electrolyte such as normal water, impurities released by chemical reactions with cell components or added with the lithium, CO₂ picked up from the air[230], or impurities present in the D₂O⁷ may affect the reaction or introduce

7. Solids at 16 ppm were detected in a bottle of D₂O supplied by Aldrich Chemical Co. and 9 ppm in a bottle supplied by MSD Isotopes[333].

errors in the heat measurement. The presence of copper or solder in contact with the electrolyte results in impurity deposition on the cathode.[250] Impurities in the Pt anode will also be slowly leached out and deposited along with Pt. All of these factors will affect reproducibility.

II.E.2 Palladium Cathode:

Purification by vacuum annealing is a common practice. Excess heat has been obtained from both vacuum annealed as well as 'as received' metal. While removing dissolved hydrogen, annealing will also change the physical structure of the metal. Reproducibility can not be expected until the structure is standardized to that which allows the effect to occur. On the other hand, heating Pd in air will remove carbon from the near surface region, thereby removing one of the components that may help the Cold Fusion effect in an aqueous cell[250]. Heating and melting the metal with a propane torch seemed to have no detrimental effect when the metal was used in a fused salt cell[234]⁸. Cleaning palladium with acids containing chlorine may not be advisable because this element is a strong poison that inhibits reaction with hydrogen. Commercial palladium contains a variety of impurities. Some of these (Rh and Ag) migrate to, and concentrate at, the surface during electrolysis[334]. Until the effect of these impurities is known, only the purest palladium should be used.

II.E.3 Correction for Electrochemical Energy Loss:

An open electrolytic cell loses energy when the D_2 and O_2 gases leave. The amount of this energy can be subtracted from that entering the cell in various ways. The most common is to multiply the thermoneutral potential⁹ by the cell current and subtract the resulting energy term from the electrical energy flowing into the cell. Minor variations in the thermoneutral potential have been used in the various studies (1.526-1.540 V). The recommended value is 1.527V, -70.46 kcal/mol, or -294.6 kJ/mol[335]. To the extent that a value higher than the recommendation is used, the reported heat will overestimate the actual excess energy, especially at higher cell cur-

8. It is not certain whether this treatment would add or remove carbon.

9. The thermoneutral potential is the enthalpy for the formation of D_2O expressed in volts. Faraday = 96489 coulombs.

rents. This quantity is accurate as long as only D_2O is being electrolyzed. In practice, some H_2O is present in the heavy-water and this is electrolyzed preferentially. Therefore, the actual neutral potential will be slightly smaller than the above value depending on the amount of normal water present. This error also will cause an over reporting of the excess heat. The normal-water concentration in heavy-water cannot be based solely on the amount claimed by the manufacturer because new bottles can differ from this claim and normal water can be picked up during the experiment. Furthermore, hydrogen from normal-water will enter the palladium preferentially[151; 314; 336] and reduce or stop excess heat production if the quantity is excessive. Closed cells do not suffer from this problem.

II.F. Nuclear Products Associated With Heat Production

In order to learn whether neutrons or tritium are associated with heat production, these nuclear products must be detected while excess heat is being generated. Many measurements have been made in the absence of excess heat production and these will be discussed in the next section. Attempts to detect neutrons and tritium during heat production have had mixed success. Tritium has been detected in cells while producing heat by Gozzi et al.[231], Fleischmann and Pons [1], and Bockris et al.[3]. During the latter study, heat had been produced for about 10 days before bursts of tritium were observed. In no case is the detected tritium sufficient to account for the observed excess heat. On the other hand, Miles et al.[243], Lewis and Sköld[242], Zahm et al.[163], Scott et al.[229], and McKubre et al.[225] did not detect tritium in their cells after heat production even though it was sought.

Scott et al.[229] reported low level neutron and γ emission from a cell making excess heat. Lewis and Sköld[242] reported neutron bursts both during and after heat production. On the other hand, Salamon et al. [172] did not detect neutrons or γ -rays from cells being studied by Pons and Fleischmann. It is not clear whether these cells were actually producing excess heat during the examination although, based on other work, this may not be a critical point. Zahm et al.[163] detected neither neutrons nor γ -rays while excess heat was being observed.

The only detected nuclear product that is clearly associated with heat production is ^4He . These studies gave the following general results.

Morrey et al.[177] (group effort): Various pieces of palladium supplied by Fleischmann and Pons, both used and unused, were analyzed for ^4He and ^3He . The work established that once helium enters the lattice, even by α -particle bombardment, it is retained. Surface helium can be removed by etching. Unfortunately, there was sufficient ^4He in the unused palladium that production in the used metal could not be established. No ^3He was detected.

Liaw et al.[316] (Univ. of Hawaii, USA): Electrodes used in a fused salt cell were analyzed for ^4He . One of four samples showed ^4He at 14σ above background. The other three samples were only slightly above background. The amount of ^4He detected was not sufficient to account for the observed excess heat.

Bush/Miles et al. [240] (U. of Texas and Naval Weapons Center, USA): Sufficient ^4He was detected in the evolving gas to account for the observed excess heat within a factor of 10. Blank cells showed no ^4He . No ^3He was detected. Helium retained by the electrode was not determined.

III. TRITIUM, NEUTRON, AND RADIATION PRODUCTION

Attempts have been made to detect neutron, tritium, γ -ray, proton, ^3He and ^4He as likely nuclear products. Of these, neutron detection has been given the greatest effort although it is the more difficult measurement because of the generally low emission rate. In addition, shifts in the $^6\text{Li}/^7\text{Li}$ ratio and the palladium isotopic ratio have been sought[334]. Techniques, such as particle track[161; 176; 302; 337] and autoradiography[225; 247], have been used to detect high energy particles but these techniques can not be used for identification.

If tritium and neutrons are actually produced in a metal lattice, the existence of at least two nuclear reactions cannot be doubted. The only issues are (1) whether tritium is produced in the cell rather than entering from an outside source as contamination, and (2) whether the neutrons actually are emitted from the fusion cell rather than from cosmic-ray showers, electrical noise or other external sources. Each of these issues will be addressed in later sections. However, the detection of both neutrons and tritium at the same time by different laboratories to give an internally consistent ratio largely eliminates the possibility of chance or contamination as an explanation.

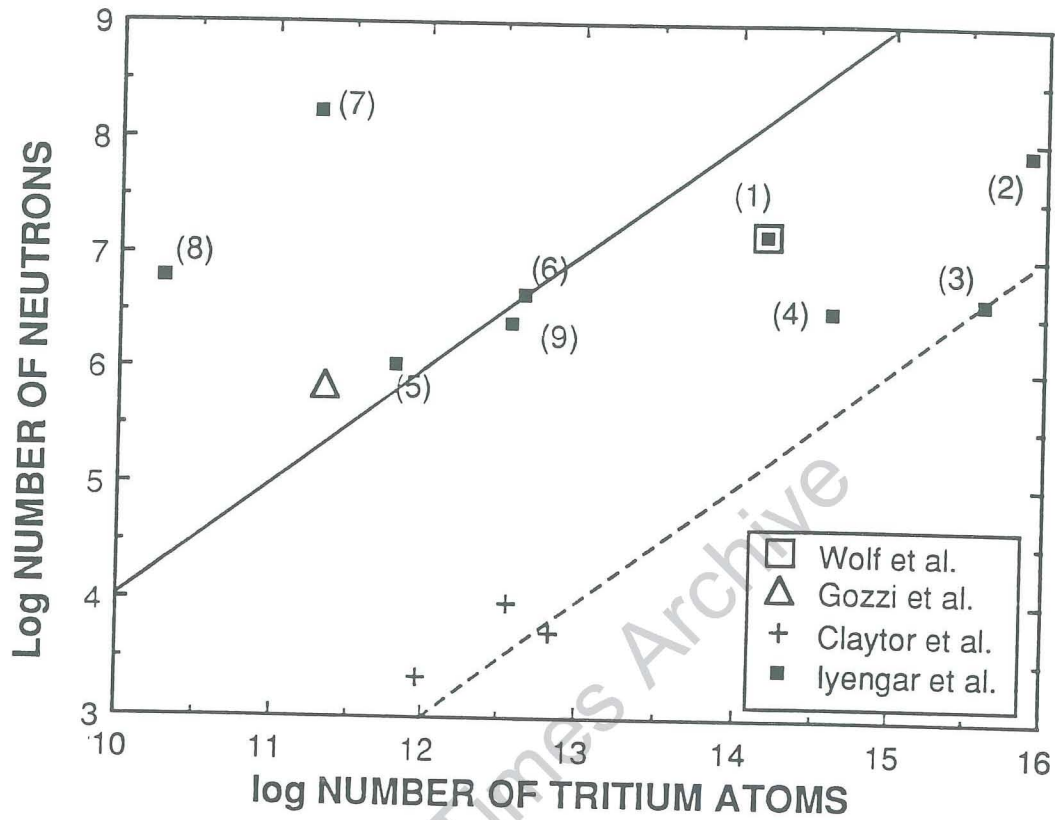


FIGURE 3 Relationship between the number of tritium atoms and the number of neutrons produced in electrolytic cells. The "+" symbol describes results from a dry electrolytic cell. A dashed line shows a constant $n/{}^3\text{H}$ ratio of 10^{-9} and the solid line shows a constant ratio of 10^{-6} . These lines do not imply a fit to the data points. Numbered points correspond to the numbering in Table 2.

III.A. Neutron/Tritium Ratio

Most workers do not have facilities available for the routine detection of both tritium and neutrons. Consequently, only a few measurements of the relative production rates have been reported. Values for the $n/{}^3\text{H}$ ratio and the cell conditions are listed in Table 2. These data are plotted as the log [number of tritium atoms] vs log [number of neutrons] in Fig. 3. Clearly, the ratio is significantly less than unity with a lower limit near 10^{-9} and it has a range of values. Indeed, low level neutron emission has been observed without the presence of tritium being detected even though it was

sought[229; 242; 272; 289; 294]. This experience suggests two neutron producing reactions. One reaction produces mainly neutrons and the other is associated with tritium production with a branching ratio near 10^{-9} . Conditions could conspire to produce a mixture of these reactions in most cells. Regardless of the interpretation, the $n/{}^3\text{H}$ ratio is clearly much less than unity, falling between 10^{-4} and 10^{-9} for a variety of cell conditions[338]. Although the $n/{}^3\text{H}$ ratio falls in a rather wide range, it seems likely to me at least that a much wider range would result if these two reactions were not coupled in some way.

III.B Tritium Production

Tritium has been detected after using at least six different methods of production. These include:

1. Wet (D_2O) electrolytic cells containing Pd,
2. Dry (SiO_2) electrolytic cells containing Pd,
3. Thermal cycling of Ti in D_2 ,
4. High voltage discharge of D_2 with a Ti cathode,
5. Ion bombardment using D_2 on Pd or Ti, and
6. Co-deposition of Pd and D onto Ni.

At least six different methods for tritium detection have been used. Each has been successful in demonstrating the presence of tritium on some occasion. These include:

1. Liquid scintillator,
2. Proportional counting of β emission,
3. Autoradiography,
4. Beta excited K_α X-ray from Ti,
5. Mass spectrometer¹⁰, and
6. Si surface-barrier particle detection of ejected triton.

III.B.1 Comparison of Reported Results

Table 2 lists the various reports of tritium production. The amount of tritium listed is a crude estimate in some cases because insufficient detail was provided.

10. Kay et al. [339] have pointed out the pit falls of this technique.

TABLE 2

Reported tritium production and $n/{}^3\text{H}$ ratio

REFERENCE	$n/{}^3\text{H}$	TRITIUM, μCi [1]	CELL DESIGN
Wolf et al.[264] ^[2]	10^{-7}	≈ 7	Pd in LiOD
Claytor et al.[252]	2.7×10^{-9}	0.17	Pd+Si(SiO_2) in D_2
	$0.8(\pm 1) \times 10^{-9}$	0.32	Pd+Si(SiO_2) in D_2
	$2.4(\pm 4) \times 10^{-9}$	0.044	Pd+Si(SiO_2) in D_2
Iyengar et al.[247]	(1) 10^{-7}	7	Ti(rod) in NaOD
	(2) 10^{-8}	380	Pd-Ag(tube) in NaOD
	(3) 10^{-9}	190	Pd-Ag(disc) in NaOD
	(4) 8×10^{-9}	1.9	Pd(tube) in LiOD
	(5) 1.7×10^{-6}	0.03	Pd(cube) in LiOD
	(6) 1×10^{-6}	0.21	Pd(pellet) in LiOD
	(7) 9×10^{-4}	0.009 ^[3]	Pd(ring) in LiOD
	(8) 3.2×10^{-4}	0.0009	Pd(coil) in Li_2SO_4
	(9) 7×10^{-7}	0.17	Pd(button) in LiOD
Sona et al.[260]	2×10^{-6} - 10^{-7}	?	Pd(sheet) in LiOD
Gozzi et al.[259]	3.4×10^{-6}	0.01	Pd(rod) in LiOD
Packham et al.[249]		0.08-340	Pd(wire) in LiOD+NaCN
Storms and Talcott[250]		0.01-0.06	Pd(wire) in LiOD
Chêne and Brass[262]		0.0005	Pd(wire) in LiOD
Sánchez et al.[268]		≈ 0.03	Ti(sheet) in Li_2SO_4
Iyengar et al. (p.57)[247]		56.3	Pd(tube) in LiOD
Iyengar et al. (p. 84)		0.007-0.03	Ti in D_2 at 900°
		0.07	Pd-Ag in D_2 at 600°
Kaushik et al. [258]		≈ 30	Ti in D_2 cycled
Chien et al. [253]		≈ 40	Pd in LiOD

[1] $1 \mu\text{Ci} = 2.2 \times 10^6$ disintegration/min. = 3.4×10^{-11} mol = 2.1×10^{13} atoms = 3.7×10^4 Bq

[2] First report of $n/{}^3\text{H}$ ratio but tritium value has since been repudiated[340].

[3] This value, obtained from a table (p. 34), is inconsistent with $16.25 \mu\text{Ci}$ given in the text (p. 52).

The rate of tritium production cannot be determined because tritium is produced in a series of bursts during the active life of a cell and the result is accumulated in the electrolyte. Most measurements are made at time intervals that are long compared to the burst interval. However, tritium production appears to occur during neutron bursts. Several of the more extensive studies of tritium production are worth examining in more detail.

Iyengar et al. [247] (BARC, India) reports a very extensive study in which tritium and neutrons are produced by electrolytic cells of various designs containing various electrolytes using Ti, Pd or Pd-Ag alloy cathodes. Tritium was also produced by gas loading Ti and Pd under various conditions. Using autoradiographs as well as other techniques, this tritium was found to occupy isolated locations on the Ti surface but is more uniformly distributed in Pd. When made by gas loading, the resulting tritium was contained mostly in the metal rather than in the deuterium gas. Tritium was detected in old Ti-D samples (10-20 y), using various techniques, at levels between 9 and 4000 μCi . However, the history of these samples is uncertain.

Storms and Talcott-Storms [250] (LANL, USA) studied a variety of surface poisons and palladium alloys in an effort to find the best conditions for tritium production. Although only a small amount of tritium was made, it was done in cells that allowed for complete inventory of tritium entering and leaving the cell. All produced tritium was found only in the electrolyte.

Claytor et al. [252] (LANL, USA) produced tritium in D_2 gas (0.001-0.32 μCi) by applying a pulsed voltage (1200-2500V, $\geq 150 \mu\text{sec}$), through alternating layers of Pd and Si discs surrounded by the gas under pressure. In eight cells out of 30, excess tritium greater than 3σ has been observed. Recent cells have shown a reproducible production rate of 0.5 nCi/hr with no production in control cells. Various techniques were used to verify that the tritium was being produced within the cell.

Packham et al. [249] (Texas A&M, USA) studied a variety of cells in an attempt to produce tritium. Levels between 0.08 and 340 μCi in the electrolyte were seen in 14 out of 28 open cells. One cell that was producing heat showed two bursts of tritium in the gas. Because this tritium was recombined and returned to the cell, the amount of tritium going only into the electrolyte is not known.

Kaushik et al. [258] (BARC, India) cycled the temperature of Ti chips in D_2 gas and found that only 4 out of over 1000 chips examined showed the presence of tritium at the $\approx 30 \mu\text{Ci}$ level.

Adzic et al [255] (Case Western Reserve Univ., USA) studied open and closed cells from which tritium production up to 49 times the starting concentration was observed. Very low charging currents were proposed to improve the probability of success.

Szpak et al. [245] (Naval Ocean Systems Center, USA) electrodeposited palladium deuteride on to copper in an open cell. Heat, tritium ($\times 10$) and X-radiation were detected. These effects were not seen in control studies. An image was recorded on X-ray film within the cell that showed that low-energy radiation

Taniguchi et al. [301] (Osaka Radiation Research Inst., Japan) did not look for tritium but did detect what appeared to be the high energy proton that accompanies tritium production. A very thin Pd cathode ($10\text{--}18 \mu\text{m}$) was electrolyzed using LiOD or LiCl in the electrolyte. A Si barrier detector on the outside of the cell measured counts up to $100\times\text{BG}$ for which the energy was determined. The energy spectrum was consistent with, although not identified as, 3 MeV protons with a lower energy component, as if they had been produced on the surface next to the electrolyte. If, as argued later, the reaction occurred on promontories, some of the protons would have had to pass through the electrolyte to reach the detector, thereby further reducing their energy.

III.B.2 Possible Errors in Claiming Tritium Production

Tritium can be present as contamination in cell materials or in the environment; various chemical reactions in the scintillator fluid can mimic the presence of tritium; and tritium can accumulate in the electrolyte as a consequence of electrolysis. Each of these possible errors will be discussed starting with the problem of contamination

Tritium can enter a cell with the construction materials and through the cell walls from room air. Both methods of contamination have been studied. Because tritium has a very low concentration in the normal environment, significant contamination from room air or from commercial materials has a very low probability. Indeed,

workers at Texas A & M[249] made a rather thorough analysis of common construction materials associated with their cells, including a number of palladium samples. They found no evidence for tritium contamination. A study of normal-water containing cells provides a method to detect tritium contamination from all sources. Excess tritium has not been reported when normal-water cells are studied.¹¹

A study of a cell operating in a high-tritium environment has been made[342]. As expected, tritium pickup is nearly linear with time starting at time zero. This is in contrast to the behavior of an active Cold Fusion cell that typically shows an initial delay followed by burst formation of tritium[249; 250; 253; 268]. Figure 4 compares the concentration of tritium as a function of time in an active and an inactive Cold Fusion cell to an identical cell stored in a high tritium environment. The patterns of tritium increase in the cells are completely different. While other cell designs are expected to have different pickup rates should environmental tritium be present, a smooth nearly linear increase is expected for all designs as tritium in the room diffuses through the cell walls or enters when the cells are opened for sampling.

The tritium might be present in the palladium electrode although the method of manufacture largely rules out this possibility[343]. Of the hydrogen isotopes, tritium has the least tendency to remain in palladium[344] when it is heated to temperatures used for processing, forming or annealing. Nevertheless, Wolf at Texas A & M reports finding tritium in two pieces of unused palladium wire as well as in an annealed electrode after it was used in a normal-water Cold Fusion cell¹². This contrasts with a very complete study[345] using 45 samples of palladium from a variety of sources, including the source used by Wolf. This work did not find any evidence (± 3 dpm/ml, 99%; confidence = $\pm 12\%$ of background) for tritium contamination in the examined palladium but did find that certain conditions during the analytical procedure would cause an **apparent** presence of tritium. Even if tritium were present in the palladium cathode, it would quickly leave the metal¹³ and appear in the evolving D_2 gas (>95 %) during electrolysis[314]. This behavior is in sharp contrast to its delayed pro-

11. However, neutron production has been reported from a light-water cell[341].

12. No tritium was detected in the electrolyte of this cell.

13. The loss is a first-order reaction with a half-life between 12 and 24 hrs depending on the charging current and the condition of the palladium.[314]

duction¹⁴ and subsequent retention in the electrolyte during most successful cold fusion experiments.

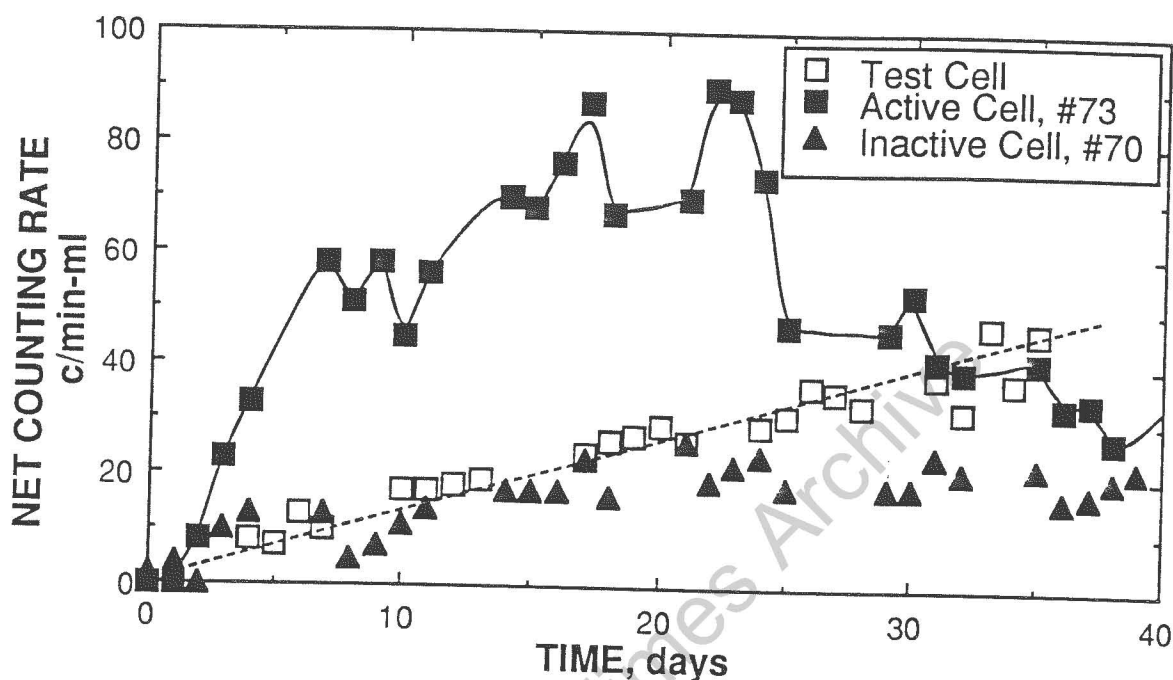


FIGURE 4. Comparison between the net counting rate in an active cell, an inactive cell, and a cell stored in a high tritium environment as a function of time from the onset of the respective studies. The net counting rate was obtained by subtracting the counting rate of the solution before the studies were started. Cells #70 and #73 were in series and the increase in tritium content of cell #70 was owing to enrichment which should affect cell #73 as well. The environment in which the test cell was placed contained ≈ 50 times more tritium than the environment of cells #70 and #73.

These considerations indicate that the tritium reported to have been made by Cold Fusion is very unlikely to have been caused by contamination of the cell or the palladium. Of course, it is impossible to "prove" that the observed excess tritium is not caused by contamination. However, when a number of laboratories make suffi-

14. A delay of several weeks was reported by Wolf.^[264] before tritium was observed in certain cells.

cient tritium by a variety of techniques using a variety of materials with a similar pattern of production, the argument for contamination as the source of tritium becomes increasingly difficult to justify.

Tritium can also accumulate within the electrolyte during electrolysis because the evolving D_2 and O_2 gases contain approximately $1/2$ as much tritium as does the electrolyte¹⁵. Consequently, the tritium content of the electrolyte in an open cell will nearly double after extended electrolysis. Equations describing this tritium increase have been published [3; 153; 157; 247; 250; 260; 346; 347]. Of course, closed cells containing a gas recombiner will not show this effect.

Chemiluminescence is caused by the presence of certain impurities in the scintillator fluid used to detect tritium. Some scintillator fluids are more sensitive to this effect than others. Because, the effect generally decreases with time after the sample is mixed with the fluid, the effect can be separated from the true presence of tritium. Nevertheless, this is an area where care needs to be taken. However, this effect cannot be used to dismiss all claims for tritium production because most workers take the effect into account, and tritium has been detected using other techniques not subject to this problem. Further discussion about tritium measurement can be found in an article by Dehn[348].

III. C. Neutron Production

Of the various aspects to the Cold Fusion effect, the production of neutrons has been studied the most thoroughly. Neutrons have been produced after using at least 7 different techniques. These include:

1. thermal cycling of Ti, Pd and $YBa_2Cu_3O_7$ in D_2 ,
2. pulsed electrolysis,
2. wet (D_2O) electrolytic cells containing Pd or Ti,
3. dry (SiO_2 or Al_2O_3) electrolytic cells containing Pd,
4. ion bombardment over a range of energies (50 eV to 60 keV),
5. sudden release of D from Pd,
6. chemical reactions in D_2O [349], and
7. physical breakup of deuterided $YBa_2Cu_3O_7$.

15. This ratio applies to Pd cathodes in alkaline solutions.

Neutrons have been detected using at least 7 techniques.

1. ^3He detector,
2. BF_3 detector,
3. detection of n, γ reaction in water,
4. ^6Li glass combined with a scintillator,
5. photon recoil scintillation spectrometer,
6. fission track detector using film containing uranium, and
7. neutron activation of silver.

Each of these production and detection techniques has been successful in demonstrating the presence of neutrons on some occasion. When the energy of the emitted neutrons is measured, values near 2.45 MeV[2; 264; 269; 270; 279; 291] as well as peaks near 4 and 6 MeV[270] are found. Neither neutron emission nor tritium was detected when Pd-D and Ti-D were bombarded with muons[204; 207; 211].

Errors in neutron measurement involve the detection of extra neutrons caused by cosmic ray showers and electrical noise in the detector circuits. Most people who have studied the Cold Fusion effect are aware of both problems. However, when the counting rate is low, it is hard to be sure that neither of these problems is occurring[350] unless extra precautions are taken. These precautions include:

1. keep the mass low around the detector to avoid cosmic ray spallation events,
2. compare the results to an identical but inert cell,
3. measure the background while the Cold Fusion cell is being studied,
4. use a cosmic-ray sensitive veto counter,
5. make the measurements underground,
6. use multiple counters,
7. use anticoincidence noise rejection. and
8. use a sensitive detector (>10%) and determine the sensitivity using a standard source.

A number of studies have now given positive results during which all of these precautions were employed. High counting rates and especially counting that is correlated with another measurement are easier to believe than a single, low level experience. Such correlations have been observed.

TABLE 3
Summary of Neutron Measurements

REFERENCE	METAL	METHOD	DETECTOR	EFFICIENCY (percent)	B.G. (c/s)	EXCESS
NEGATIVE RESULTS						
Aberdam[202]	Pd,Ti	electro.	⁶ Li Scin.	2.3	2x10 ⁻⁵	0
	Ti	60 atm				0
	Ti ₄ Ni ₂ O	60 atm				0
Abriola[189]	Pd	electro.	Ge,BF ₃		?	<13
Albagli[150]	Pd	electro.	BF ₃ ,NaI	0.02-0.03	0.7	0
Alber[195]	Pd	electro.	NE213., BF ₃	?	0.02	0
Aleksan[201]	Pd,Ti	electro.	⁶ Li Scin.	12.5	7x10 ⁻⁴	<0.014
Baurichter[190]	Pd	electro.	Ge, Scin.		?	<20
Barwick[176]	Pd,Ti	15 atm	CR-39	na	na	0
Brudanin[222]	Pd	electro, gas	BF ₃ ,Ge	0.32	8x10 ⁻⁴	0
Brudanin[221]	Ti	electro,gas	BF ₃ ,Ge	0.32	8x10 ⁻⁴	0
Behrisch[175]	Ti	implant.	Sur. Barrier			0
Besenbacher[208]	Pd,Ti	bombard.	Scin.			0
Blagus[210]	Pd	electro.	⁶ Li Scin.	0.5	?	<0.2
Blencoe[290]	Pd	<38 atm	BF ₃	6	0.16	0
	Ti	<38 atm	BF ₃		0.148	0.164?
Broer[351]	Pd	electro.	NaI	1.5	1	0
Brudanin[219]	Pd,Ti	electro.	BF ₃	0.3	10 ^{-3,-5}	0
		gas				
Brudanin[302]	Pd	electro.	CR39, Si			0
Bruschi[216]	Ti	<1 atm	NE213	1.3	?	0
Butler[194]	Pd,Ti	electro.	³ He	9.2	0.0028	0
Campbell[213]	TiD	IR heat	NE213	?	?	0
Davies[207]	Pd,Ti	muon	NE213			0
Deakin[184]	Pd	electro.	X-ray	0.0039	0.0003	0
Dignan[186]	Pd-Ir	implant.	NaI	0.0004		0
Ehrlich[203]	Pd	electro.	B Prop.	2.6	0.016	0
Ewing[194]	?	gas	³ He	9.2-15		0
Faller[162]	Pd	electro.	Ge		40(γ only)	0
Gottesfeld[178]	Pd	electro.	³ He, NE213	16	0.005	0
	Ti	53 atm				

Table 3, Continued

REFERENCE	METAL	METHOD	DETECTOR	EFFICIENCY	B.G.	EXCESS
Guilinger[160]	Pd,TiT	electro.	^3He	1.3-4	0.0017	0
Hajdas[180]	Pd	electro.	NE213, BF_3	0.006	0.0001	0
	LaNi_5	12 atm	NaI, NE102			0
Henderson[187]	Pd,Ti	electro.	NE213, NaI	?	0.1-0.7	0
Hill[188]	Pd	electro.	Ge, BF_3	0.35	0.01	0
	Ti	50 atm		0.28	0.01	0
Ilic[161]	Pd	electro.	^3He , CaF_2	0.14	?	0
			CR39, Ge			
Kamm[209]	Ti	12-62 atm	B Prop.	0.123	0.029	0
Kashy[206]	Pd,Ti	electro.	NE213(2.5MeV)	1.		0
Kocsis[223]	Pd,Ti	electro.	^3He	6.3	0.002	0
Kuzmann[217]	Fe-Zr	electro.	BF_3 , NE213			0
Lewis[148]	Pd	electro.	^3He , Ge	14-20	0.2	0
McCracken[155]	Pd	electro.	^3He , BF_3 , NaI	1.6	0.0083	0
	Ti	40 atm			0.0083	0
Myers[174]	Pd,Ti,Zr	implant.	particle			0
Porter[164]	Pd	electro.	Ge, ^3He , NE213	1.3	0.058	0
Rehm[166]	Pd	electro.	particle	28	0.001	0
Salamon[172]	Pd	electro.				0
Schirber[197]	Pd,Ti	<2.4 kbar	^3He	≈ 9.2	0.0028	0
	$\text{Ti}_{0.8}\text{Pd}_{0.2}$	50 atm			0.0028	0
	Zr,V	50 atm			0.0028	0
Schrieder[167]	Pd	electro.	particle			0
Silvera[179]	Pd	105 kbar	BF_3	0.09	0.0006	0
Southon[193]	TiT	electro.	NE213(14 MeV)	2.5	0.0006	0
Vielstich[220]	Pd	electro.	NE213(2.5MeV)	43	0.0012	0
Werle[198]	Ti	50 atm	^3He	10	0.8	0
Ziegler[170]	Pd	electro.	particle	≈ 100	5×10^{-5}	0
POSITIVE RESULTS						
Bertin[269]	Ti	electro.	NE213(2.5 MeV)	4	0.055	0.3xBG
Celani[267]	Pd	electro.	^3He , NaI	1		4-16xBG
Claytor[252]	Pd	electrodisc.	^3He	1.3	0.2	3-8 σ
De Ninno[256]	Ti	50 atm	BF_3	0.005	0.00064	35xBG
Fleischmann[1]	Pd	electro.	BF_3	0.024		3xBG

Table 3, Continued

REFERENCE	METAL	METHOD	DETECTOR	EFFICIENCY	B.G.	EXCESS
Govorov[295]	Pd-Sm Pd-Ru	1 atm	^3He	10.5	?	1.9xBG
Gozzi[231]	Pd	electro.	NaI(γ)	0.005	0.0008	180xBG
Granada[275]	Pd	electro.	^3He	17.5	0.001	6 σ
Gu[278]	Pd	bombard.	BF_3	?	0.033	10xBG
Harb[289]	Pd	electro.	^6Li	0.53	0.002	2xBG
Iyengar[247]	Pd,Ti	electro. gas, discharge	$\text{BF}_3, ^3\text{He}$		variety	
Izumida[288]	Ti	20-50 atm	$^3\text{He},$ BF_3	0.5 0.02	1.7×10^{-2} 2.8×10^{-4}	>3 σ >3 σ
Jianyu[297]	Ti	gas	^3He	20	0.005	<75xBG
Jorne[276]	Pd	60 atm	NE213	1	0.03	2xBG
Jones[279]	Pd	electro.	^6Li Scin.(2.2.5MeV)		0.001	3.5xBG
Karabut[236]	Pd	discharge	^3He	5	0.1-0.01	10^8 xBG
Lewis[242]	Pd	electro.	^3He	8	0.2	2-10xBG
Lin[287]	Pd	electro.	$^3\text{He}, \text{BF}_3, \text{Ge}$	?		≈ 30 xBG
Lin[337]	Pd	9 atm	CR-37, CaF_2	na	na	tracks
Lipson[293]	Ti	$\text{D}_2\text{O}(\text{mill})$	?		0.05	6xBG
Menlove[271]	Ti	1-40 atm	^3He	21-44	0.2-0.03	3-9 σ
Miljanić[280]	Pd,Ti,V	electro.				3 σ
	Pd	electro.	NE213,LiI	0.04	0.0077	3xBG
	Ti	25 atm	BF_3	0.01	0.00055	5xBG
Perfetti[284]	Pd,Ti	electro.	^3He	1	0.03	4xBG
Prelas[281]	Pd	bombard.	$\text{BF}_3, \text{Scin.}$			2-4xBG
Rout[248]	Ti	discharge	Ag		na	10^6 - 10^8
Sánchez[268]	Ti	electro.	BF_3, NaI	?	0.00056	$\leq 2 \times 10^4$
Sato[277]	Pd	electro.	^3He	7	0.025	3xBG
Scott[229]	Pd	electro.	NE213, NaI	0.146	0.0009	3xBG
Seeliger[285]	Pd	electro.	NE213, 2.5 MeV			5xBG
Sinha[296]	Pd,Ti	electro.	$^3\text{He}, \text{NaI}$	?	0.003	4-6xBG
Sona[260]	Pd	electro.	$^3\text{He}, \text{BF}_3$	0.02	0.0013	<3.3xBG
Shani[286]	Pd	3Kg/cm ²	NE213			
Takahashi[291]	Pd	electro.	$^3\text{He}, \text{NE213.}$	0.17	0.019	≈ 70 xBG

Table 3, Continued

REFERENCE	METAL	METHOD	DETECTOR	EFFICIENCY	B.G.	EXCESS
Takahashi[270]	Pd-Ag	electro.	^3He , NE213		0.04	1.4xBG
Wolf[264]	Ti	67 atm	NE213(2.5MeV)			0
	Pd,Ti	electro.		5	0.013	3.8xBG
Yagi[282]	Ti	gas	NE213	0.13	0.003	3 σ
Yagi[352]	SiO ₂	gas	NE213	0.13	0.003	3 σ
Yamaguchi[266]	Pd	gas	BF ₃			$\approx 10^5$ xBG

Explanation of Headings

METAL: The elements, alloys, or compounds are listed.

METHOD: Material studied in an aqueous electrolysis cell is indicated by "electro."; a dry electrolysis cell by electrodisc.; gas loading is generally designated by the pressure of the D₂ gas; and "discharge" and "bombard." designate the use of high voltage discharge in low pressure D₂ and bombardment by high energy ions, respectively. When in D₂ gas, the material was generally cycled with respect to pressure and/or temperature.

DETECTOR: Frequently, variations in the listed detectors were used. In addition to neutron detection, many workers made provision to find γ -rays by using the listed detector. The ^3He and BF₃ detectors are sensitive only to near-thermal neutrons while the various scintillators such as NE213, and ^6Li combined with NE213 can be used to determine the energy of both neutrons and γ -rays within a wide energy range. Pulse-height measurement is used to distinguish between neutron and gamma emission. Detectors made from germanium (Ge) or NaI are sensitive to γ - and X-rays. Frequently, two detectors are used to eliminate the possibility of spurious counts in one detector being interpreted incorrectly.

EFFICIENCY: The stated value for neutron/count, expressed as percent, is listed. The value is only for the neutron detector. Occasionally, several configurations were studied, giving multiple values for the efficiency. The smaller the value, the more likely small emission rates would be missed.

BACKGROUND: The background is given as c/s only for neutron detection. In some cases, a variety of values were observed depending on the configuration. This value as well as the listed efficiency can only be used as a rough guide to the sensitivity.

Table 3, Continued

ty of the detection system. The original paper needs to be consulted for more detail.

EXCESS: Excess neutron detection rate is expressed as a multiple of background or sigma above background. Generally, a range of values was reported depending on the particular experiment.

Two regimes of neutron production are observed; (1) average rates less than 1 n/s over a relatively long time with burst behavior, and (2) rates near 10^6 n/s for a short time. The large difference in these rates suggests either two separate nuclear reactions or an occasional high concentration of the special condition. A very high D/Pd ratio, by itself, does not seem to be sufficient to cause neutron production. Low level neutron emission from thermal cycled titanium in pressurized D_2 has been duplicated by at least five independent, carefully done studies. Numerous studies showing how neutron emission is coupled to various parameters are discussed in detail as follows.

Jones et al [2] (BYU, USA) produced low level neutron emission at 2.5 MeV by electrolyzing Pd in an electrolyte containing a complex mixture of metal salts. Bertin et al.[269] (U. of Bologna, Italy) used Ti as the cathode instead of Pd and obtained essentially the same result.

De Ninno et al. [256] (Frascati, Italy) cooled titanium chips in high pressure D_2 to liquid nitrogen temperature. Neutron bursts were observed when the assembly was warmed to room temperature. This is the first report of this phenomenon. Menlove et al. [271] (LANL, USA) repeated the procedure and observed that bursts of neutrons had a high probability of emission ($3-12\sigma$) near -30° C. No effect was found when normal hydrogen or Pd in place of Ti was used. This effect was also seen by Izumida et al. [288] (Hitachi, Japan) who found a $>3\sigma$ increase in count rate between -53° and 0° C. Iyengar et al. [247] (BARC, India) also observed neutron emission (up to 200 n/s) when Ti was held in D_2 (10 atm) at 77 K and warmed during evacuation. Jorne [119] (U. of Rochester, USA) placed palladium in D_2 gas at 90 atm and -80° C. When warmed slowly, neutron and γ -ray bursts occurred as the temperature changed between ≈ 500 K and 600 K. No effect has been found in any of these studies when

normal hydrogen was used. Jianyu et al. [297] (China Inst. Atomic Energy, China) thermal cycled Ti and Pd in pressurized deuterium gas using an underground laboratory. Seven out of 10 assemblies gave bursts of neutrons (3-75xBG) between -100° C and room temperature using Ti, but not when Pd was used.

Sona et al. [260] (CISE SpA, Italy): Palladium sheet was charged from one side using a Pd anode in an electrolytic cell. The neutron signal started increasing when the current was started and this steady increase lasted for 400 min and reached 4 times background. Over the next 400 min, the signal dropped and reached background where it remained for 41 h after the current had been stopped.

Granada et al [275] (Centro Atomico Bariloche, Argentina): An electrolytic cell having a Pd cathode was subjected to altering current on-current off conditions (≈ 2 minute cycle). Neutron production was highest at about the center of the current on time and near the center of the current off part of the cycle. Repeated cycles reduced the effect. Neutron production was about 0.3 n/sec. Takahashi et al. [291] (Osaka U., Japan) also produced neutrons from Pd (0.017 n/sec, $1.4 \times \text{B.G.}$) using the pulsed-current technique (19 minute cycle). They found the best LiOD concentration to be 0.6M. Perfetti et al. [284] (Frascati, Italy) found neutron emission from both Pd and Ti cathodes when a 1 h on-1 h off cycle was used. Mathews et al [292] (Indira Gandhi Center, India) found a current increase to cause increased neutron production in a cell containing a Ti cathode with palladium and nickel salts in a D_2O electrolyte. Arata and Zhang [241] (Kinki U. and Osaka U., Japan) were able to produce bursts at average rates exceeding 10^8 n/s by cycling the current off and on. In this case, the cathode consisted of a rod of Pd (2 cm dia) attached to a gold-plated bar of Ti.¹⁶ On the other hand, neither Blagus et al. [210] (Ruder Boskovic Inst., Yugoslavia), using much shorter cycles (2 Hz, 2.2 mHz and 0.56 mHz), nor Aiello et al. [214] (U. di Catania, Italy), using loading and unloading in D_2 gas, produced neutrons.

Iyengar et al.[247] (BARC, India): This paper contains a large variety of observations during which neutrons were detected from Pd, Pd-Ag, Ti, and Ni-Ti electrodes using LiOD or NaOD in the electrolyte. Steady production as well as large bursts were measured. Neutron production was correlated with γ -ray and tritium production. Pulsing the current between 1 and 2 A during part of a cell history

16. It is not clear which metal, the Pd or the Ti, caused the neutron burst.

seemed to encourage production of nuclear products.

Gozzi et al. [231] (Univ. of Rome, Italy): A sudden increase in cathode (sintered Pd powder) temperature ($>120^{\circ}\text{C}$) was correlated with a burst of neutrons (7.2×10^5). In this case, it is not known whether the heat rise caused conditions that produce neutrons or, on the other hand, a nuclear event produced neutrons and caused a temperature rise.

Yamaguchi and Nishioka [266] (Musashino-shi, Japan): A sheet of Pd (1mm thick) was coated on one side with Mn-O and on the other with gold. After being held for a day in 0.5 atm D_2 at room temperature, the sample was placed in vacuum. Within about 3 h, an explosive release of deuterium occurred that was associated with a burst of neutrons ($1-2 \times 10^6 \text{ n/s}$). Sudden heating caused alloying between the gold and palladium. Repeated cycles using the same sample produced similar neutron bursts but after a shorter time in vacuum. Neutron production and heat were not observed while using normal hydrogen. This heat can not be caused simply by loss of the small amount of contained D_2 gas because this reaction is endothermic.

Bém et al. [353] (Inst. Nucl. Phys., Czechoslovakia): A thin layer of titanium ($1.4-1.7 \text{ mg/cm}^2$ on Mo) that had been reacted with tritium showed low level neutron production at 14 MeV when it was used as a cathode in an electrolytic cell. On the other hand, **Guilinger et al. [160] (Sandia Nat. Lab., USA)** failed to find evidence of fusion using a thin film of TiT on Cu in an electrolytic cell, and **Southon et al. [193] (McMaster U., Canada)** detected no neutrons after a larger piece of Ti had been heated in T_2 gas and electrolyzed. However, there were other major differences between these studies besides the thickness of titanium that could account for the different results.

Sánchez et al. [268] (Dept. Física Aplicada, Spain): Titanium was electrolyzed in a cell containing Li_2SO_4 in D_2O . Bursts of neutrons (up to 4×10^4 times background) were correlated with changes in cell current, γ -ray detection (2-2.3 MeV) and tritium production. The neutron rate dropped in a linear manner after the cell current was turned off.

Lipson et al. [293] (Inst. Phys. Chem. USSR): Ball milling Ti with D_2O or deuterated polypropylene caused neutron emission ($0.3-0.4 \text{ c/s}$) during the process, for a short time (8-10 min) afterward, and when the material was cooled in liquid nitrogen. Repeated cycles caused the effect to disappear.

Silvera and Moshary [179] (Harvard U., USA): An important negative study was done at very high pressures (105 kbar) using thin Pd (97 μm thick x 208 μm diameter) in D_2 gas. A D/Pd ratio of 1.34 ± 0.1 was claimed. This is much higher than any other reported value. However, the Pd had been pressure bonded to Re, an operation that would have severely disrupted the periodic array of atoms within the lattice. Detection sensitivity was not sufficient or stable enough to be able to conclude that energy was being produced although there was a slight indication of excess heat (<2.3 mW). No neutrons were observed above the 1.86 ± 0.3 c/h background and no effort was made to detect tritium. Fractofusion¹⁷ is not possible under these conditions, although heat and/or tritium production might have been possible but their production was inconclusive.

Shani et al. [286] (Ben Gurion U. and Hebrew U., Israel): Studies of gas loaded Pd and high pressure D_2 suggest that the emission of 2.5 MeV neutrons is enhanced by an external source of neutrons.

III. D Gamma-Ray and Other Emissions

Many workers have examined cells with γ -ray detectors. However, only a few have detected γ -rays and this was only while some other aspect of the Cold Fusion effect was occurring. Because normal water is usually present, some, if not all, of the γ -rays may result from neutron-proton interaction to give a 2.2 MeV signal. A calculated, idealized γ spectrum produced by the 2.45 MeV neutron energy associated with D-D fusion has been published[354].

Scott et al. [229] (ORNL, USA): Gamma rays were measured while neutrons were being emitted and heat was being produced. Counts were seen between 2.61 and 3.14 MeV with no increase outside this range down to 2.12 MeV or above 5.2 MeV. Correlation between γ and neutron emission also has been reported by **Celani et al. [267] (Italy)** for γ energy between 100 and 500 keV, and >800keV; **Jorne [276] (U. of Rochester, USA)** for γ energies >360 keV; and **Sánchez et al.[268](Dept. Física Aplicada, Spain)** for energies between 2 and 2.3 MeV. **Iyengar et al.[247] (BARC, India)** measured correlated neutron and γ emission (1.186 MeV and > 3 MeV) in a variety of cells. **Bush/Miles et al. [240] (U. of Texas and Navel Weapons Center, USA)** detected

17. Fractofusion is fusion that is proposed to occur when cracks form in the metal hydride.

electromagnetic radiation while heat was being produced using X-ray film.

Matsumoto [298] (Hokkaido U., Japan): Tracks were seen in nuclear-sensitive film located on the outside of a cell containing a Pd cathode and an electrolyte of 3% NaCl in D_2O . The shape of the tracks was used to argue for a new particle called "iton".

Jones et al. [355] (BYU, USA) detected charged particle emission from deuterium loaded Pd foils that showed clear energy peaks. Because the inferred energy depends on an uncertain knowledge of the type of particle, the absolute energy is unknown.

III.E Nuclear Products from Bombardment or Implantation

Nuclear products have been produced by bombarding palladium or titanium with deuterium. Energy has been added to the atoms by using high voltage discharge, ion acceleration, or acceleration of D_2O or D_2 clusters. These techniques add energy to the deuterium atoms before they contact atoms residing in the metal lattice, resulting in what is called "lukewarm fusion" by some workers. Although some fusion is expected to be produced by such high energies, a large quantity of products, a low $n/^3H$ ratio, and sustained emission after bombardment has creased have been observed and are not expected. On the other hand, some experiments did not produce unexpected results.

III.E.1 High Voltage Discharge

Karabut et al.[236] (Scientific Industrial Association, Russia): Heat and neutrons were produced using discharge in D_2 gas with a Pd cathode. The purity of the surface was found to be important. A similar study by **Besenbacher et al. [208] (U. of Aarhus, Denmark)**, during which the Pd was covered by 50Å of Cu, failed to produce neutrons. Palladium, after being silver-soldered in air to copper, also failed to produce results in a discharge cell (**Ruzic et al. [304] (U. of Illinois, USA)**). **Prelas et al. [281] (U. of Missouri, USA)** formed a microwave plasma in D_2 (0.5-10 eV) which was caused to impact on Pd metal. Evidence for low level neutron and gamma emission (2-10x BG) was obtained while the plasma was operating. A γ -ray peak centering on 8.1 MeV was observed during one experiment after a lengthy discharge.

Rout et al. [248] (BARC, India) subjected Ti to plasma discharge of D_2 in a Mather plasma focus device[356] that produced ion energies in the range 10-100 keV. This technique produced significant amounts of tritium (up to 392 μCi) and a very low $n/{}^3\text{H}$ ratio ($<10^{-5}$).

III.E.2 Ion Bombardment

Chambers et al. [300] (NRL, USA), after several previously reported negative attempts, detected the emission of particles that were consistent with the presence of high energy tritons (≤ 5 MeV) after bombarding Ti with 300-1000 eV deuterons. The magnitude of the emission and its continuation for up to 6 min. after the beam had been turned off are not consistent with expectation. Behrisch et al. [175] (Max-Planck Institut für Plasmaphysik, Germany) found that bombardment of Ti by 4.5 keV D_3^+ failed to produce detected reaction products.

Cecil et al. [299] (Colorado School of Mines, USA) bombarded thin films of Pd (1 μm) deposited on to Mo (3 μm) using 95 keV D^+ . Evidence for emitted 3 MeV photons and 1 MeV tritons was obtained during the bombardment. After the bombardment was stopped, when the foil had been sufficiently implanted with D, a current was passed through the foil. Particle emission, assumed to be protons, was detected near 3 MeV and 5 MeV. Later studies[357], using Ti implanted with D followed by several thermal cycles, produced large bursts of activity that were inferred to be 10 MeV tritons or ${}^3\text{He}$. The presence of any emission during such a treatment, but especially its energy, are unexpected. Gu et al. [278] (Mississippi State U., USA) observed neutron production (9x BG) while bombarding Pd with 1 keV D^+ . Neutron production was also observed by Durocher et al. [196] (U. of Manitoba, Canada) using 60 keV D^+ . However, in the latter case, the flux was claimed to be consistent with known fusion theory. Further studies reported by McKee et al.[358] (U. of Manitoba, Canada) showed neutron emission from Pd and Ti targets when loaded with D using 60 keV D^+ and 30 keV D_2^+ . Myers et al. [174] (Sandia National Laboratory, USA) detected nearly equal proton and triton emission while bombarding Pd, Zr, and Ti with 10 keV D^+ , but found no emission after the beam was turned off. Dignan et al. [186] (San Francisco State U., USA) bombarded a thin film of Pd ($\approx 2000\text{\AA}$) with 1 keV neutral D and D_2 at 77 K and found no evidence of emitted neutrons or 23.8 MeV γ -rays.

III.E.3 Cluster Bombardment

Beuhler et al.[305] (Brookhaven National Laboratory, USA) bombarded TiD, ZrD, and polydeuteriopolyethylene with clusters of D_2O containing 20 to 1500 molecules accelerated to 200 to 325 KeV. A maximum in the resulting photon counting rate occurred when the cluster size was near 200 D_2O molecules. The fusion rate was much larger than expected from conventional theory and larger abundances of ^3H and ^1H were seen in the spectrum compared to ^3He , thereby giving an apparent branching ratio of $<0.88^{18}$. Such studies fall in the transition region between hot fusion and cold fusion. This work has been discussed in detail by Rabinowitz/Kim et al. [359] (EPRI, Purdue U., and SRI, USA) in a series of papers.

Fallavier et al. [306] (Institut de Physique Nucléaire de Lyon, France) used clusters of frozen deuterium ions in the size range between $(200D)^+$ and $(300D)^+$. Bombardment of TiD and polyethylene targets using an energy of 100 to 150 KeV produced no evidence for fusion.

IV. DISCUSSION

During the last two years, all of the observations made by the original discoverers of the cold fusion effect have been confirmed by numerous observations throughout the world. In addition, many new conditions have been discovered that cause the effect to occur. In spite of this effort, many people find a major problem in accepting the Cold Fusion effect because there is a lack of expected nuclear signatures, the magnitude of the effect is much larger than expected based on current theory, and there is still difficulty in replication. As a result, various arguments are proposed to attribute the heat to chemical processes, the tritium is explained as contamination or experimental error, and the neutrons are assumed to be caused by cosmic rays or instrument error. These explanations had reasonable basis during the early history of the field. Now, the variety of techniques and accuracy of the work make this approach much less tenable.

18. This value is an upper limit because of an uncertain base-line for the ^3He peak caused by the residual X-ray background.

When d-d fusion occurs, the reaction products can be tritons (^3H), protons (H), helium (^3He), and neutrons. Based on considerable experience with "hot" fusion, these reaction products should be produced in negligible quantity, or at least in nearly equal amounts, and be accompanied by X-radiation. To the extent that neutrons form, γ -radiation (2.22 MeV) should also be seen from n-p interaction with the surrounding water bath. The absence of significant neutrons as well as the absence of any expected nuclear product sufficient to cause the observed heat has added to the skepticism. In addition, the apparent absence of 14 MeV neutrons resulting from t-d (^3H - ^2H) fusion is a concern to some. Because of these apparent conundrums, the field is still handicapped by considerable doubt and limited support in many countries.

Neutrons are now known to be produced as bursts ($\approx 10^3$ - 7 n/s) as well as at a steady but lower rate (<1 n/s). When measured, the expected energy for d-d fusion of 2.45 MeV is found along with neutrons near 3 and 7 MeV. Neutrons in unexpectedly large quantity have been found to issue from Pd, Ti, or several alloys after being loaded with deuterium by gas reaction, electrolysis, or ion bombardment. Nonequilibrium conditions, such as produced by temperature changes, increase the probability of production although an overt creation of nonequilibrium is not always a requirement. Physical commutation (ball milling) of Ti in a deuterium containing media and chemical reactions involving deuterium containing compounds also can result in neutrons. In some cases, neutrons seem to result from fracturing (fractofusion) of the material lattice. Although titanium is known to easily fracture when it hydrides, this effect is less obvious in palladium. Nevertheless, fissures are produced in palladium during electrolysis[360;361] and each time it is cycled through the α - β transition[314].

Values for the n/ ^3H ratio fall, at the present time, between 4×10^{-4} and 10^{-9} using electrolytic Cold Fusion cells. Using conventional techniques, the expected branching ratio for d-d fusion is near unity for impact energies at least as low as 3 keV[362; 363; 364] and for muon fusion at even lower energy[365; 366]. Ion impact studies of Buehler et al. [305] near 100 eV indicate a slightly less than unity branching ratio. A variety of approaches have been used to explain this apparent conflict. Kim [104] argues that the muon fusion data are not applicable and suggests either that the branching ratio is nonlinear to give smaller n/ ^3H values at lower energy or there is some resonance enhancement for tritium production in the low energy region. Resonance be-

tween deuterium atoms has also been proposed by Zakowicz and Rafelski [68]. Mayer and Reitz [107] argue that a variety of resonance reactions are possible between deuterium and various impurity metals and these reactions can result in preferential tritium production. On the other hand, Chatterjee [121] suggests that the branching ratio is very sensitive at low energies to the energy available in the final nuclear products after energy is drained off into the lattice electrons. This idea is extended by Hora et al. [103] using a proposed electron surface layer as the medium for screening and energy extraction. Collins et al. [118] suggest that a tunneling process in the lattice leads to an excited state of ^4He that decays primarily by the production of tritium, a proton and energetic electrons. Handel [89] also suggests a tunneling process which involves neutron transfer. If a source of virtual neutrons were available in the system or real neutrons were supplied from the outside, Kim [115] suggests that the $n + ^6\text{Li} = ^4\text{He} + \text{T}$ reaction might be the source of both tritium and helium without the production of neutrons. In a more novel model, Hagelstein [111] proposes that a virtual, coherent interaction between a deuteron and a proton occurs, and that this not only makes tritium but also deposits the resulting energy into the lattice, thereby solving two problems. Finally, polarization of the two D nucleons by the Oppenheimer-Phillips [367]¹⁹ process is proposed by several authors[90] to distort the reaction branches toward tritium production at very low approach energy. Using a statistical model, Bush [338] calculates a value of 1.64×10^{-9} for the $n/^3\text{H}$ ratio. This brief summary does not exhaust all of the published suggestions but is included to show that a variety of hypotheses have been proposed to explain the low $n/^3\text{H}$ ratio. Of course, there is no universal agreement as yet. On the other hand, there is general agreement that the fusion rate is extremely sensitive to the energy of approaching deuterons for the energies involved in the Cold Fusion process[106]. In addition, the two branches for D-D fusion may have different sensitivities to energy in this low energy region if deuteron polarization is important. Therefore, when energy is added to the deuteron, the fusion rate will increase and the $n/^3\text{H}$ ratio may change. Proposed processes that add energy are fractofusion, energy amplification at the tips of dendrites on the surface, a high-energy tail to the Maxwell velocity distribution[47], and phase changes[46; 102] that

19. Polarization of the deuteron was proposed to explain the unexpectedly high transmutation function during nuclear reactions between D and Na, Al, Si, and Cu. [368].

add kinetic energy to the deuterons. These processes add a relatively small amount of energy and would be important only if the fusion process were very sensitive to the deuteron energy. Much more energy can be added outside the metal environment by gas discharge or ion bombardment. Whether these processes can add sufficient energy to explain the observations depends on the chosen nuclear model. In addition, the $n/{}^3\text{H}$ ratio may have a spectrum of values if the deuterons have a variable energy or if several different nuclear reactions occur simultaneously. A mainly-tritium reaction is proposed when the least energy is added and a more neutron-rich product when the greatest energy is added.

The expected 14 MeV neutrons appear to be absent. These neutrons would result if fusion produces high-energy tritons that fuse with environmental deuterium. Even if energy measurements are lacking, the resulting neutrons should, nevertheless, add to the general neutron flux. Consequently, the $n/{}^3\text{H}$ ratio should be at least 10^{-5} even if no other neutrons were being made during tritium production. The absence of this neutron flux suggests that tritons are being made with insufficient energy to initiate d-t fusion. This energy reduction would result if the nuclear energy were coupled to the lattice in some way. In one case[353], 14 MeV neutrons were measured after tritium was placed in a cell in advance of the cold fusion reaction. This unique positive result demonstrates that when correct conditions are present to allow fusion to take place, d-t fusion can occur and the reaction produces neutrons of the expected energy. This result does not demonstrate that 14 MeV neutrons will result following d-d fusion.

Other types of radiation are expected and have been sought. High energy particles, when passing through a metal lattice, must produce X-rays. However, these X-rays have very low energy and, consequently, are difficult to detect unless special provisions are made. Exposure of X-ray film located near the cathode has been reported in a few cases[240; 245] but a quantitative study made during X-ray emission has yet to be reported. However, there have been several unsuccessful attempts to detect X-rays.

The initial skeptical reaction was to assume tritium resulted from contamination. A great deal of effort has been devoted to showing that contamination is not an important factor and how contamination, if it should occur, would behave in an electrolytic cell. The tritium observed in a cold fusion cell does not act like tritium that is

known to be present as contamination[314]. Tritium has now been made in electrolytic cells having a variety of electrolytes and cathode metals, by gas loading Ti, and by voltage discharge in low pressure D_2 gas. It has been detected using scintillator fluid, proportional counting, K_α X-ray emission, and autoradiography. Amounts up to 380 μCi and over 10^5 times background have been produced on several occasions. Although it is not possible to prove that contamination is not present, dismissal of all claimed tritium production based on contamination can no longer be supported by fact. If this assertion is to be made believable, it needs to be backed up by evidence rather than opinion.

Heat has been produced near 450°C at rates up to 25 W, which is over 10 times the cell input energy rate. Typical cells at room temperature have excess energy production rates between 7 and 300%. In most cases, this rate is over a factor of 10 above the sensitivity or uncertainty in the calorimeter measurements. Because of the care used in the design of more recent studies, dismissal of excess heat based on accumulated or absolute error is no longer tenable. The energy production rate shows a linear increase with cell current up to about 700 ma/cm^2 where it has a predicted production rate of 2.5 W/cm^2 . An increase in temperature to $\approx 450^\circ\text{C}$ results in a factor of 10 increase. Of course, the total amount of energy produced by a cell depends on how long the cell is run after excess energy production starts. Some cells stop production before the patience of the researcher has been exhausted. Other cells are reported to have produced a total energy greater than 10 MJ. The energy production rate and the total energy obtained from a significant number of cells is far in excess of that produced by any conceivable chemical reaction. Indeed, if this ^{large} excess were produced by chemical reactions, the discovery is ~~now~~ as important as if nuclear reactions were involved. Neutrons and tritium are seldom detected while heat is being produced and, when seen, the amounts are much too small to account for the excess heat. Recent detection of ^4He after two studies[316; 240] of heat production adds support to the conclusion that excess heat is caused by a nuclear reaction.

The lack of reproducibility in the Cold Fusion effect is tied directly to a difficulty in creating the required conditions within the lattice or on the surface of the host metal. Regular success can not be expected until many electrodes have been examined in detail to determine the conditions that both produce and do not produce the effect. In addition, a detailed understanding of the chemistry, metallurgy, and solid-

state physics of many metal hydrides, not just palladium, is essential. Even palladium, which has been studied extensively for years[369], still reveals new variables that affect its interaction with hydrogen.

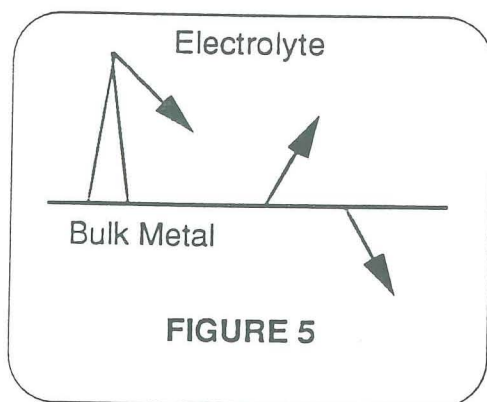
IV.A. Do Nuclear Reactions Take Place on the Surface or in the Bulk?

A first step toward understanding the Cold Fusion effect is to determine where nuclear reactions occur. Is it a bulk or a surface effect? Perhaps a combination occurs depending on the particular nuclear reaction and on the method used to add deuterium. The behavior of tritium can reveal the origin of the tritium-neutron reaction and the behavior of helium can be used to understand the heat producing reaction.

IV.A.1 Tritium Production

Tritium that is located within bulk palladium will exit an electrolytic cell with the evolving gases[314]. Only tritium that forms on the surface can enter the electrolyte and then only if it is released by nuclear recoil energy. These conclusions are based on the behavior of tritium that was placed in a palladium cathode and then followed as it left an electrolytic cell. Because all observed tritium has been found in the electrolyte, except for one report[370], it is reasonable to conclude that tritium is produced on the surface of the cathode. If this tritium is on the bulk surface, at least 1/2 will recoil toward the bulk material and subsequently appear in the evolving gases. The remainder will enter the electrolyte. This nearly 50-50 distribution between gas and electrolyte is not observed. Therefore, the tritium does not appear to form on the bulk surface. To be consistent with observation, we must conclude that tritium forms at the tips of dendrites²⁰ or promontories located above the surface, as first suggested by Bockris[372], supported by Rabinowitz and Worledge [373], and developed further by Kim[106]. In this location, the solid angle toward the metal structure is sufficiently small so that most of the emitted tritons pass into the electrolyte rather than into the metal. Figure 5 shows typical recoil paths from an idealized surface and dendrite. Tritium has also been produced when Pd-D was electrodeposited[245], a process that would be expected to produce a rich supply of dendrites.

20. Electrodeposition of impurities is not the only way in which promontories can form on palladium. Stress relief during changes in hydrogen content can also cause variations in surface character[371].



Tritium production, as a surface reaction, is not expected to require a high average D/Pd ratio in the bulk material. General experience is consistent with this conclusion. However, a high D/metal ratio is expected to exist in the dendrites where the fusion reaction is proposed to happen. Tritium production at this location is thought to occur because the deuterium atoms are given some additional energy by the applied cell voltage[323;

[373; 374]. If tritium actually forms on the tips of dendrites, then the nuclear reaction does not take place in palladium but in a structure created by electrodeposited impurities. Unfortunately, this suggestion adds an overwhelming complexity to the problem because the surface impurity layer is very complex[244; 334; 375; 376; 377; 378]. However, it does mean that a variety of metals may be useful as cathodes for tritium production provided the correct impurities are present in the electrolyte.

To the extent that the nuclear energy is not coupled to the metal lattice during tritium production, Bremsstrahlung X-radiation and 14 MeV neutrons should be observed. The apparent absence of 14 MeV neutrons suggests that tritium is produced with relatively little energy. If tritium forms on dendrite surfaces, methods that allow energy coupling to the metal lattice become a challenge to visualize.

When titanium or palladium are subjected to nonequilibrium conditions, such as temperature cycling after gas-loading, tritium is formed even though no dendrites are present. Both metals are known to form cracks during this process. Although titanium and its alloys are more susceptible to cracking than palladium, fractofusion[247; [324; 379; 380; 366; 381; 382; 383] is proposed to occur in both cases. During this process, deuterium atoms are given energy by the charge separation created when a crack is formed. Because the generated voltage gradient is high, (>10 keV/cm), the fusion rate and the $n/{}^3\text{H}$ ratio would be more like that expected from high-temperature fusion. In addition, the initial formation of a crack may force the deuterium atoms very close together within slip planes, thereby increasing the probability for fusion[384] without additional energy being required. However, the reaction is very brief, the crack formation rate is limited, and the total number of cracks that can form is also limited. Therefore, this reaction is not expected to produce a significant amount of nuclear

products. The small amount of tritium that is produced is expected to remain in the metal lattice during gas-loading or be swept into the evolving gas during electrolysis. Bursts of neutrons and tritium would be expected if a large number of cracks should form at the same time. Because the resulting $n/{}^3\text{H}$ ratio by this process is expected to be larger than by surface production, the relatively small amount of tritium would probably be missed by the usual detection methods. Consequently, this reaction would appear to produce mainly neutrons. However, there is no reason why this reaction and surface production could not occur simultaneously in an electrolytic cell, thereby giving a variable $n/{}^3\text{H}$ ratio.

IV.A.2 Heat Production

Helium formation appears to be associated with heat production. A small fraction of the necessary helium has been detected within the metal[316] but much more has been found in the evolving gas[240]. It is well known, that once helium is captured²¹ within a palladium lattice, it will not leave[385] except near the melting point. Therefore, for helium to be detected in the gas, it must have been produced sufficiently close to a surface so that recoil energy would allow it to be released from the lattice.²² Nuclear recoil would direct some of the helium toward the bulk where it would remain. Consequently, some helium should be found in the bulk material as has been the case. This heat-producing reaction is not expected to occur on the outer surface where tritium is thought produced because heat and tritium production are not initiated by the same conditions and seldom occur at the same time. In addition to the outer surface, there are internal environments that have contact with the evolving deuterium gas. Heat production, therefore, is proposed to occur in contact with the internal fracture system but near the outer surface where the D/Pd ratio would be sufficiently large. If this view is correct, thin films or foils of palladium should work better than bulk material because a greater fraction of the palladium would be involved in heat production and because thin films have a smaller tendency to relieve stress by crack formation. The presence of fewer cracks is proposed to result in a

21. This includes helium that might be present as a contaminate. Therefore, the detected He is not expected to result from He that might have been contained in the Pd before the experiment started.

22. This recoil energy is relatively small if the nuclear energy is coupled to the lattice as is apparently required for this reaction to occur at all.

higher average D/Pd ratio and a higher fusion rate. In addition, most of the helium should be found within the metal lattice rather than in the gas.

The effect of normal water addition on heat production is more of a problem to understand. Studies have shown that heat continues for 20 to 100 hr (see Section II.C) after normal water is added. Replacement of deuterium by protium in palladium produces some heat but hardly enough to account for the apparent excess. The deuterium replacement rate can be estimated by analogy to the tritium replacement rate. The half-life for tritium replacement by deuterium has been determined to be in the range of 12 to 24 h, depending on conditions[314]. Near-surface replacement would be completed first and should cause heat production to stop immediately. This apparent contradiction between helium behavior and water-replacement behavior could be explained by some p-d fusion taking place or by assuming that isolated regions of high deuterium concentration remain in spite of normal-hydrogen being present.

Heat production has been suggested to involve lithium which is only located on the surface. This view was supported by a study showing that replacement of LiOD by NaOD caused a loss of excess heat with a somewhat faster rate than after addition of normal water[226]. In contrast to this experience, heat production was reported using NaCl in the electrolyte[239] and by a fused salt cell[234] that does not deposit lithium on the palladium. The fact that tritium can be produced in NaOD may not be relevant to heat production because the reaction environments appear to be different. At this time, lithium does not appear to be involved in the heat-producing nuclear reaction, although its presence does seem to improve the environment for heat production.

IV.B. Ion Bombardment

The tritium- and neutron-producing branches can also be enhanced by giving deuterium additional energy using an ion beam or by gas discharge with the target being the cathode. This method should be much more neutron-rich and fusion-efficient than an electrolytic cell. Experience has shown that the target surface must be completely free of certain impurities if this technique is to succeed[236]. Consequently, the surface environment is important even when deuterium is given additional energy. Heat production has been reported on one occasion using the discharge technique but helium was not sought[236]. Neutron production is said to have been sufficient to

account for the observed heat if a small branching ratio is assumed. Because tritium and helium production were not reported, the true relationship between nuclear products and heat is still unknown in this case.

IV.C Effect of Metal Environment

Because pure palladium was used successfully during the early work, it has been given particular attention. Later studies have shown that fusion can be obtained using palladium alloys as well as titanium. However, because fusion is apparently produced by more than one process, the results have been somewhat different between various metals. Titanium seems to be more likely to produce neutrons during thermal cycling than does palladium. On the other hand, palladium, but especially Pd-Ag alloys, seem more likely to give tritium and neutrons in an electrolytic cell. A variety of alloys, elements, and physical forms have been studied including Pd (both polycrystalline and single-crystal), Pd-Li, Pd-C, Pd-S, Pd-B, Pd-Be, Pd-Rh, and Pd-Rh-Li[250]; La-Ni[180]; Fe-Zr[217]; Ti-Pd, Zr, and V[197]; Pd-Sm and Pd-Ru[295]; Ti-Ni-O[202]; Pd-Ir[186]; Pd-Ag[247; 270]; SiO₂[352] and V[271]. Only SiO₂, Ti, Pd (drawn, rolled, hammered, annealed, and electrodeposited), Pd-Sm, Pd-Ru and Pd-Ag have given evidence of a fusion reaction. Heat has been reported using titanium as well as palladium although palladium appears to be the better choice for this aspect of the Effect. The presence of large amounts of those elements that are normally present in palladium as low-level impurity do not improve the reproducibility of the effect. Therefore, nuclear reactions involving these elements seem unlikely.

Rather special and difficult to reproduce conditions are an essential feature of the Cold Fusion effect. To the extent that nuclear reactions occur on the surface, the environment will be complex and not involve the base metal directly. Therefore, those variables that affect the surface and those impurities that reside on or are plated onto the surface need increased attention. On the other hand, heat production seems to be sensitive to the bulk properties of the metal.

Palladium has been found to show several unusual effects that might be relevant to heat production. In passing completely into the β -phase, excess volume is created[314]. This process continues without apparent limit each time the material is cycled between the α - and β -phases after being within the β -phase. Measurements of AC resistivity and capacitance of palladium cycled in this manner indicate that rifts or

fractures are formed and these contain a significant amount of ionized[361] hydrogen under high pressure[386]²³. Detailed visual examination shows fractures of various sizes and shapes mainly associated with grain boundaries[387]²⁴. These fractures open and close depending on the charging or discharging conditions. During electrolytic charging, a flux of deuterium flows into the surface, through the metal and is exhausted from the electrode through that part of the fracture system connecting to the surface[314]. Thus, even under steady-state conditions, the metal hydride is not at equilibrium. Furthermore, the high-pressure, ionized deuterium gas present in the closed rifts is sensitive to current flowing through the palladium.²⁵ This fracture system offers an additional environment, consistent with helium-loss experience²⁶, in which the heat producing reaction might occur. This general behavior suggests that attention needs to be paid to the interior surfaces of palladium as well as to its outer surface.

IV.D Proposed Nuclear Reactions

With very few exceptions, all of the effects attributed to Cold Fusion require the presence of deuterium. For a nuclear reaction to occur, either two deuterons must fuse together or a deuteron must fuse with some other nuclei such as a proton or a metal. A conclusion based on d-p fusion is made less likely because the presence of normal water eventually stops the reaction without producing an increase when the protium concentration in the palladium just begins to increase²⁷. Interaction with a metal nucleus may be possible but seems unlikely to be the ~~main~~ reaction because, excepting for palladium, other metals are present in very low and highly variable concentrations. When these impurities were added in higher concentration, no improvement in reproducibility was observed. In addition, evidence for helium generation during heat production is starting to be accumulated. Consequently, d-d fusion re-

23. J. Dienes gives a theoretical analysis of formation conditions for internal fracture[384].

24. The author of this paper propose that this facture system is partly caused by the fusion reaction and the fusion reaction causes the size of the voids to grow. At the present time, there is no supporting evidence for this viewpoint.

25. It is worth noting that the addition of deuterium to the rift and dislocation system is expected to be slightly exothermic[388]. Hence this energy is not an important source of heat that might be mistaken for nuclear energy.

26. For helium to be found in the evolving gas, it must be produced on or very near a surface that is in contact with the evolving gas.

27. After D₂O is replaced by H₂O, the H/D ratio in the palladium will slowly rise over several hours with the fastest change taking place in the near-surface region.

mains the simplest explanation consistent with most experimental data. The observations of different combinations of heat, tritium and neutron production are proposed to result from a different combination of the three branches for this fusion reaction. These branches are:

1. $D(d,n) {}^3\text{He}$,
2. $D(d,p) {}^3\text{H}$, and
3. $D(d, \text{energy}) {}^4\text{He}$.

This explanation requires that each branch be sensitive to different conditions within or on the surface of a metal and that each branch couple most of the resulting nuclear energy to the lattice. While there is also some evidence for other reactions involving neutron transfer to the palladium and/or metallic impurity atoms, this does not seem to be the main source of heat or tritium. Nevertheless, these possibilities suggest that several nuclear reactions might be catalyzed by a metal lattice under special conditions.

VI. CONCLUSION

It is easy to dismiss one or even a few observations of unexpected behavior that can not be reproduced. This is done routinely by scientists during their work because most of such observations usually are caused by unknown errors. However, when many measurements, using a variety of techniques, are found to give similar results and begin to reveal patterns of behavior, the observations can no longer be ignored. This situation now exists in the Cold Fusion field. It is now far easier and more rational to begin the process of understanding Cold Fusion as a real phenomenon rather than finding ways to dismiss it. In spite of early difficulties, useful theoretical models are being constructed and the work is gradually becoming reproducible. Unfortunately, the number of important variables is so large, the necessary diagnostic equipment is so expensive, and the general support is so minimal that a clear and convincing understanding will be very slow in coming.

At the present time, heat production equal to at least 10 times the input energy has been achieved. This magnification is well above break-even on a laboratory scale. The heat effect appears to involve mainly the near-surface rather than the entire bulk material and it has a limited lifetime in present cells. Consequently, a possibility exists for considerable magnification of the effect should ways be found to involve a greater fraction of the metal for a longer time. This potential provides an important incentive for possible commercial application. The low availability and high cost of palladium may not be a limitation as first thought provided the effect can be made to occur in thin films. If this phenomenon can be developed to the level of commercial usefulness, heat could be produced without the formation of significant undesirable products now associated with nuclear as well as combustion energy. Even 'hot fusion' is not as benign nor as far above break-even after years of study as is 'Cold Fusion'. In addition, tritium might also be produced under different conditions without the large number of radioactive products that are a byproduct of current methods. During this time of environmental concern, these possibilities are extremely important and should not be ignored.

A large fraction of the limited resource has been devoted to proving that Cold Fusion is real in contrast to understanding how it works. Except during the early euphoria, support has been minimal in many countries. As a result, many people have continued to do excellent work in spite of very little support from the scientific institutions or their peers, with a few exceptions. Although there are still many uncertainties, I suggest that the possible applications are so important and the present evidence for the reality of the effect is so strong that a more optimistic attitude and more support are warranted.

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Addresses

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The First Annual Conference on Cold Fusion

National Cold Fusion Institute
390 Wakara Way
Salt Lake City, Utah 84108,(\$55 to NCFI)

Anomalous Nuclear Effects in Deuterium/Solid Systems

Prof. S. E. Jones
Physics Department
Brigham Young University
Provo, Utah 84602,(\$55 to S. & J. Scientific Co.)

Cold Fusion Symposium of the World Hydrogen Energy Conference #8

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